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Plug-and-Train Robot (PLUTO) for Hand Rehabilitation: Design and Preliminary Evaluation

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ABSTRACT Hand neurorehabilitation involves training movements at the forearm, wrist, fingers, and thumb joints. Assisted training of all these joints requires either one complex multiple degree-of-freedom (DOF) robot or a set of simple robots with one or two DOF. Neither of these is economic or clinically viable. This paper addresses this problem with the **PLU**g and train r**O**bot (PLUTO)- a single DOF robot that can train multiple joints one at a time. PLUTO has a single actuator with a set of passive attachments/mechanisms that can be easily attached/detached to train for wrist flexion-extension, wrist ulnar-radial deviation, forearm pronation-supination, and gross hand opening-closing. The robot can provide training in active and assisted regimes. PLUTO is linked to performance adaptive computer games to provide feedback to the patients and motivate them during training. As the first step towards clinical validation, the device usability was evaluated by 45 potential stakeholders/end-users of the device, including 15 patients, 15 caregivers, and 15 clinicians with standardized questionnaires: System Usability Scale (SUS) and User Experience Questionnaire (UEQ). Patients and caregivers were administered the questionnaire after a two-session training with the robot. Clinicians, on the other hand, had a single session demo, after which feedback was obtained. The total SUS score obtained from patients, clinicians, and caregivers was 73.3 ± 14.6 ($n = 45$), indicating good usability. The UEQ score was rated positively in all subscales by both patients and clinicians, indicating that the features of PLUTO match their expectations. The positive response from the preliminary testing and the feedback from the stakeholders indicate that with additional passive mechanisms, assessment features, and optimized ergonomics, PLUTO will be a versatile, affordable, and useful system for hand rehabilitation.

INDEX TERMS Hand rehabilitation, rehabilitation robot, usability.

I. INTRODUCTION

Hand impairments resulting from a multitude of neurological and musculoskeletal conditions can significantly affect ADL such as feeding, self-care, etc., and have a debilitating effect on a person's quality of life. Every year, 15 million people are affected by stroke worldwide, and 1.5 million people in India [1], about 80% of stroke survivors need some form of hand rehabilitation [2]. Incomplete tetraplegia is second only to stroke; the incidence of spinal cord injury (SCI) is estimated at 10 to 83 per million per year worldwide, with a significant proportion of those under the age of 25 years [3]. It is reported that 48.7% of the people with tetraplegia indicated that regaining hand functions is essential and of greatest priority to improve their quality of life [4]. Cerebral palsy (CP) is the most prevalent disability in children, occurring in 2.13 out of 1000 live births [5]. Almost 50% of children with CP present with a hand dysfunction [6].

Hand rehabilitation requires patients to train various joints, including the wrist, forearm, fingers, thumb, etc. Hand rehabilitation includes a mix of passive, active, and resistive exercises, which help to recover hand strength and dexterity.

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TABLE 1. Features of Most Common Hand Rehabilitation Robots(.) Legend WFE: Wrist Flexion Extension; WURD: Wrist Ulnar Radial Deviation; FPS: Forearm Pronation Supination; ABAD: Abduction/ Adduction; HOC: Hand opening closing.

	Device Name	No. of Actuators	Functions Trained
Simple Robots	SUE [7]	2	WFE and FPS
	Singh et al. [8]	1	Combined Wrist flexion and finger extension
	WRed [9]	1	WFE or WURD
	Nam et al [10]	2	FPS and Hand Grasp
	Haptic Knob [11]	2	HOC and FPS
	Higuma et al. [12]	2	WFE and WURD
	HEXORR [13]	2	MCP FE and Thumb ABAD
	Aabdallaf et al. [14]	2	WFE or WURD
	Zhou et al. [15]	1	Pinch
	BiManu Track [16] *	1	WFE or FPS
	HandSOME [17]	1	HOC
Complex Robots	WristBot [18] *	3	WFE, FPS, WURD
	NU Writst [19]	3	WFE, FPS, WURD
	Rice Wrist [20]	3	WFE, FPS, WURD
	Physiotherabot[21]*	3	WFE, FPS, WURD
	Hand of Hope [22] *	5	Finger opening closing
	Rutgers Master II [2]	4	Haptic finger opening closing
	GIFU [23]	18	Thumb FE, THUMB ABAD, Individual Finger FE
	AMADEO [24] *	5	Finger FE

* Commercially available robots

Passive training/exercises involve repetitive joint movements across the joint's range of motion to stretch the soft tissue and mobilize the hand. In passive training, the patient is fully relaxed, and movements are fully assisted. This type of training reduces joint stiffness, edema [25] and improves proprioceptive acuity [26]. Active training is a crucial ingredient for recovery following neurological rehabilitation[27], [28], where the patient performs all movements voluntarily to complete therapy tasks; when a therapist or a robot provides some external assistance, this is referred to as active-assisted training. Resistive training is an extension of active training where voluntary movements are made against external resistance. It has been reported to increase strength, tone, mass, and endurance [29]. Depending on the patient's impairment level, a mix of active(-assisted), passive, and resistive exercises are prescribed.

Recent studies have shown that targeted high-intensity training can reduce impairments and increase functional activity in multiple disease conditions [30]–[33]. However, in stark contrast to this evidence, the current rehabilitation dose is reported to be as low as 53 active movements and 32 functional repetitions every session across the entire upper limb in traumatic brain injury and stroke [27]. Similarly, a study with 103 SCI inpatients reported that the median upper-extremity repetitions in people with paraplegia and tetraplegia were 7 and 42 repetitions, respectively [34]. Several factors are responsible for this state of affairs: (a) growing patient population, (b) high patient to therapist ratio (as high as 25000:1 in India [35]), (c) limited healthcare budget [36], (d) the long duration of rehabilitation programs, etc.

Rehabilitation robots can address some of these problems by providing intense, engaging, semi-automated therapy with intermittent, direct/remote supervision from a therapist [37]. In the last 15 years, various hand rehabilitation robots have been developed and evaluated. A systematic review in 2010 found 30 devices capable of training hand rehabilitation [34], and in just six years, by 2016, the number of designs published has increased to 165 [35]; some of these existing hand rehabilitation robots are listed in Table 1. A more recent advancement is using soft robots for hand rehabilitation [38]–[44].

We classify the existing hand rehabilitation robots based on the number of actuated degrees-of-freedom (DOF) in the robot:

a) **Simple robots** are ones with 1 or 2 actuated DOF. These robots have relatively low engineering complexity, are affordable, and are easier to develop, manufacture, and use. However, these robots are designed to only train one or two specific hand functions.

b) **Complex robots** are one with more than 2 actuated DOF. These robots can train multiple joints or functions simultaneously. These are more intricate devices from an engineering viewpoint and are relatively more expensive.

A complete robotic solution for hand neurorehabilitation will either require a set of simple robots to train different

FIGURE 1. PLUTO framework.

hand functions or one complex robot that can train all these functions. Both are not viable solutions for meeting the needs of hand neurorehabilitation in-clinic or at home. Soft robots have higher flexibility, are safer, lighter, and are potentially cheaper. However, soft robots for hand training have some of the limitations as traditional robots, where assisted training of different hand functions would require multiple actuators or multiple soft robots. Additionally, most soft robots are wearables/gloves; the donning and doffing of these devices can pose practical difficulties.

Unsurprisingly, the penetration of rehabilitation robots into clinical practice has been limited [36], with very few commercial robots for hand rehabilitation [37]–[40]. One of the primary reasons for this is the affordability of existing rehabilitation robots [41], [42]; most existing devices are prohibitively expensive for the number of features they offer.

One possible solution to this problem is to have a hybrid between the simple and complex robots, which will be easy to use, affordable, and allow us to train multiple hand functions individually (Fig. 1). Such a solution can be realized through a robot with a single actuated DOF to which different passive mechanisms can be easily attached/detached, where each passive mechanism is designed to train a particular joint movement or function. The goal of the work presented here was to develop and evaluate such a robot, which we refer to as the **Plu**g and **T**rain R**o**bot (PLUTO) for hand rehabilitation.

The present work makes several important contributions to the rehabilitation robotics literature:

(a) It demonstrates the possibility of using the simplest possible robot for training multiple important hand functions. This is the simplest robot because it uses a single actuated DOF and does not require any change to the robot's structure to train different functions. There is some prior work in such a hybrid approach for a hand rehabilitation robot using a single-DOF robot to train multiple functions of the hand. Khor *et al.* recently presented – the CR2-Haptic [45], which uses a single actuator and changeable handles to train wrist/forearm functions. The work presented here on PLUTO pushes the capabilities of this hybrid approach by overcoming the short-comings of the CR2-Haptic: (1) CR2-Haptic's table-mounted actuator needs to be rotated for training different functions (e.g., switching from wrist flexion-extension to forearm pronation-supination requires rotation of the actuator by 90 degrees). Another close commercial system is the E-link Upper limb exerciser (Biometrics Ltd.) which uses a modular plug-and-play type approach like PLUTO and CR-2 Haptic. However, this system does not provide assisted training of hand functions.

(b) It demonstrates the possibility of training gross hand opening and closing function using this single DOF robot, an important class of movements for functional independence [46], [47]. No other existing simple robot can train wrist, forearm, and hand movements.

(c) The usability of a robot is a crucial factor for the acceptance of a robot for clinical practice. Patients, their caregivers, and clinicians are three important stakeholders in the neurorehabilitation process. Thus, this study investigated PLUTO's usability by all these stakeholders, making it the only study to have tested a system for these three stakeholder groups.

This paper presents the technical details of PLUTO's mechanical hardware, control design and characterization, performance-adaptive games, and the outcomes of a multi-stakeholder usability study carried out with the robot. The focus of the current work was to showcase and highlight some of the use cases of a simple, single actuator system for hand neurorehabilitation. Part of this work was submitted to the BioRob2020 conference [48].

II. PLUTO ARCHITECTURE

PLUTO's design objective was to build a compact, portable, and versatile hand rehabilitation robot with the potential for easy integration into clinical practice. PLUTO (Fig. 2) uses a single actuator with an open/free output shaft. Various passive (no sensors or electronics) single-DOF mechanisms can easily be attached to this output shaft for training different wrist and hand functions; the passive mechanism's design determines the function trained with the robot. PLUTO's current version can train the following four functions (Fig. 2(b)-1(d))

1. Wrist flexion/extension (WFE)
2. Wrist ulnar/radial deviation (WURD)
3. Forearm pronation/supination (FPS)

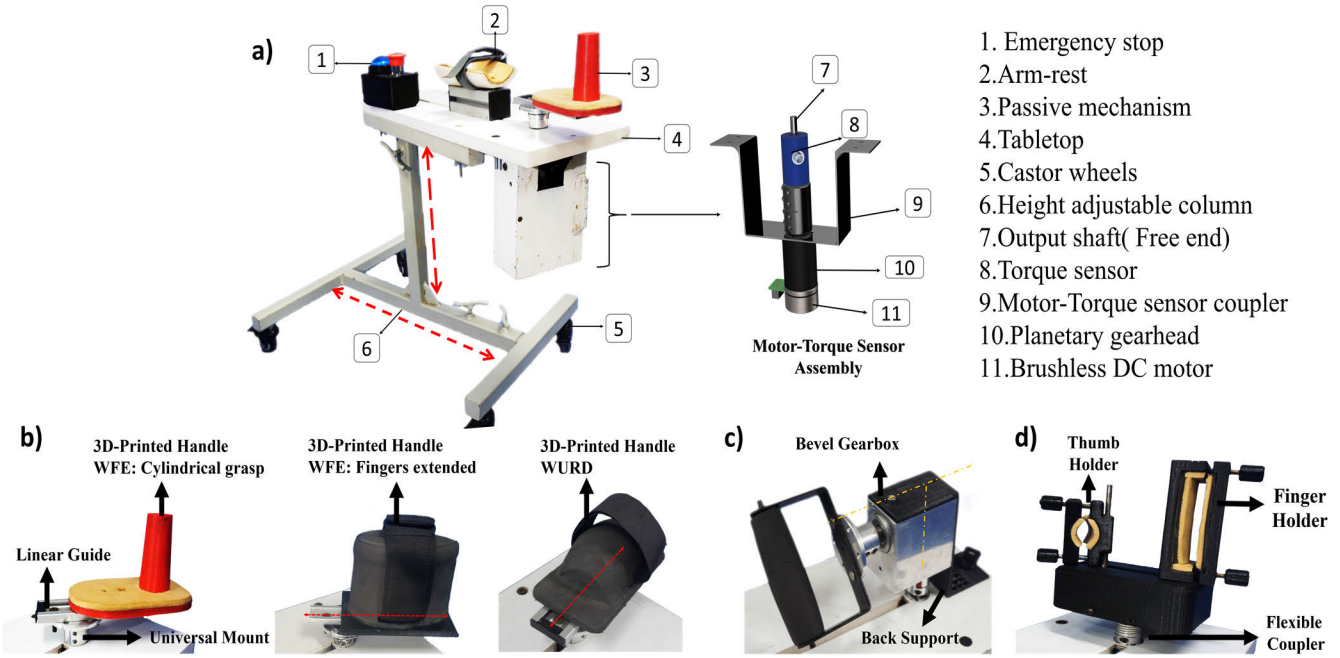

FIGURE 2. PLUTO Design a) PLUTO height adjustable trolley setup and motor torque-sensor assembly b) Wrist mechanism: Wrist Flexion-Extension and Wrist Ulnar-Radial Deviation (WFE and WURD) c) Pronation-Supination(FPS) mechanism d) Hand opening-closing (HOC) mechanism.

4. Gross hand opening and closing (HOC)

Table 2 summarizes the recommended force/torques and range of motion (ROM) for the four different wrist/hand functions (data obtained from [49]–[51]), along with the corresponding capabilities of PLUTO. The robot is mounted on a portable custom-designed trolley with provisions to adjust the tabletop's height to accommodate different wheelchairs and beds. Detailed illustration of PLUTO with the dimensions of the trolley and additional illustrations of the mechanisms can be found in the supplementary file (Fig. 2) and the supplementary video. Note, the term ''hand function'' is used in this paper to refer to both the wrist, forearm, and finger functions.

A. PASSIVE SINGLE DOF MECHANISMS

All mechanisms have a universal mount/shaft coupler that can be fastened to the robot's output shaft. The WFE and WURD mechanisms consist of a linear guide with the universal mount at one end. The linear guide's carriage houses the handle to which the subject's hand is attached. The prismatic DOF in the linear guide accounts for any offset between the axis of rotation of the human wrist and the actuator. WFE and WURD only differ in the design of their handles.

The FPS mechanism consists of a 1:1 bevel gear (Pitch diameter 25 mm, module 1.5) to rotate the axis of rotation by 90 degrees; the flexible couplers account for small misalignments between the robot and the human joint axes.

The HOC mechanism converts the actuator's rotary motion into a translational motion using a rack-and-pinion (pitch diameter 60 mm, module 1). A single pinion mates with two racks placed at diametrically opposite sides, translating in opposite directions when the pinion rotates. This translational motion is used for assisting power grasp-like movements. The FPS and the HOC mechanisms have back support to prevent the entire body of the mechanisms from rotating when the robot is actuated; the back support is fastened to the tabletop through a wing nut.

B. ACTUATOR AND SENSORS

A brushless DC motor (Maxon EC Flat 45, 397172, Maxon Precision Motors Inc., Switzerland.) with a 26:1 reduction (Planetary Gearhead GP 42 C Ø42 mm, Part number 203119, Maxon Precision Motors Inc., Switzerland) is used as the actuator, which has a rated torque of 3.38 Nm at 190 RPM. The motor is used in combination with a Hall sensor and a quadrature optical encoder (Maxon Encoder MILE, 1024CPT, Maxon EC Flat 45, 397172, Maxon Precision Motors Inc., Switzerland). A rotary torque sensor (FYTE 5Nm, Forsentek Inc., China) was mounted on the motor shaft to measure the interaction torque (Fig. 2A). A metal enclosure with dimensions 15 × 7 × 10 cm protects the motor-torque sensor assembly, the microcontroller, and the Maxon motor controller.

C. ROBOT FIRMWARE

A microcontroller (Arduino Due, Arduino AG) handles the robot's control, sensor data acquisition, and bidirectional USB serial (UART) data communication with the PC's therapy software. The firmware measures the robot position $\theta_a(t)$ and speed $\omega_a(t)$ from the motor's encoder and Hall sensor,

TABLE 2. Device capabilities compared with requirements ADL and the limits in healthy.

DOF	Activities of daily living		Biomechanical limits		PLUTO	
	ROM	Force/Torque	ROM	Force/Torque (Max)	ROM	Force/Torque (Max)
WFE	80-115 deg	0.35 Nm	160-170 deg	20 Nm	180 deg	3.5 Nm
WURD	40-55 deg	0.35 Nm	70-90 deg	10 Nm	180 deg	3.5 Nm
WPS	150 deg	0.06 Nm	175-180 deg	20 Nm	180 deg	3.5 Nm
HOC	-	-	15-20 cm	450N	12 cm	50-55 N

respectively, and the actual interaction torque $\tau_a(t)$ from the torque sensor.

The low-level control of the robot's motor is implemented as a servo speed controller using the ESCON 36/3 Maxon controller. The robot's interaction with a user is implemented through a torque controller as the following:

$$\omega_d(t) = k_p \cdot (\tau_d(t) - \tau_a(t)) \tag{1}$$

where t is time, $\tau_d(t)$ is the desired interaction torque, k_p is the controller gain (no units), and $\omega_d(t)$ is the desired speed input to the low-level speed controller. *Active* (or non-assisted) *training mode* is implemented by setting $\tau_d(t) = 0$ Nm in Eq. (1), while the *assisted training mode* is implemented by setting an appropriate non-zero $\tau_d(t)$; the robot can also resist movements, but this is not implemented in the current version.

D. ASSIST-AS-NEEDED (AAN) CONTROLLER

The AAN controller minimally assists a patient in reaching targets outside his/her active range of motion (AROM). AAN controller was implemented on top of the torque controller through a simple rule that learns a user-specific map $\left(\tau^{tgt} = \mathrm{T}_{AAN}\left(\theta^{tgt}\right)\right)$ between target locations θ^{tgt} and the assistance torque τ^{tgt} required to reach these targets. On a given movement trial of duration T sec, when the target location θ^{tgt} is presented to a subject to reach, the assistance torque corresponding to this target is applied using a sigmoid function.

$$\tau_d(t) = \frac{\tau^{tgt}}{1 + e^{2\cdot(t-0.4T)}}, t \in [0, T] \tag{2}$$

The AAN algorithm updates the assistance $\mathrm{T}_{AAN}\left(\theta^{tgt}\right)$ for the target θ^{tgt} on a trial-by-trial basis depending on whether a subject can consistently reach the target θ^{tgt}. The detailed algorithm of the AAN controller is provided in [48].

E. THERAPY SOFTWARE

The software for a user (clinician, patient, or caregiver) to interact with the robot was developed using the Unity Game Engine (Unity Technologies). This software presents a Graphical User Interface (GUI) for the user, communicates with the robot's microcontroller to receive sensor information, controls the robot, and logs the game and robot data during therapy. The software creates a unique login ID for each patient and stores all data under this unique ID. After logging into the software, the user selects the mechanism to be used with the robot. An assessment of the patient's active range of motion (AROM) and passive range of motion (PROM) must be carried out before training with the adaptive games.

F. THERAPY GAMES

Practice is a crucial ingredient for recovery, and effective practice requires consistent, intense training, active participation, and training that optimally challenges the subject's skill [52]. To this end, training with PLUTO was gamified with games that adapted according to the patients' performance (Fig. 3). Two of the games, Hat-trick and Flappy-bird, can be played in active (zero assistance) and assisted modes (AAN), whereas the Pong game can only be played in the active mode. The games' difficulty levels were determined by the magnitude and speed of movements required to play these games, which are controlled by their difficulty parameters (Table 3). The firmware on Arduino Due runs at 100 Hz. The unity Game has a graphic update of 100-120 Hz. The round-trip delay of data sent from the PC (Unity Game) to the controller (Arduino) and back, is between 10 to 20ms.

The amount and the speed of the movement required to traverse the computer screen are determined by the game range of motion (GROM), and the game speed (ω_g) parameters, respectively. GROM sets the limits of the movements required from a subject to traverse the entire game screen. Let θ_{min}^{gROM} and θ_{max}^{gROM} represent the minimum and maximum robot angles required to move to the two extremes of the game screen. All game targets lie within θ_{min}^{gROM} and θ_{max}^{gROM}, thus the maximum possible amplitude of movement required to play the game is $\theta_{max}^{gROM} - \theta_{min}^{gROM}$. The values of θ_{min}^{gROM} and θ_{max}^{gROM} are determined from a subject's AROM and PROM, depending on whether the game is played in the active mode or the assisted mode, respectively.

The AROM and PROM are parametrized by two numbers each, corresponding to the limits of a continuous interval of joint angles. AROM is represented by the minimum $\left(\theta_{min}^{aROM}\right)$ and maximum $\left(\theta_{max}^{aROM}\right)$ robot angles that can be achieved by the subject voluntarily. Similarly, the PROM is represented by the minimum $\left(\theta_{min}^{pROM}\right)$ and maximum $\left(\theta_{max}^{pROM}\right)$ robot joint angles that the subject can safely reach when their limb is moved passively by the robot.

The GROM $\left(\theta_{min}^{gROM}, \theta_{max}^{gROM}\right)$ for a game is parametrized by a scalar γ. When a game is played under the active mode,

$$\begin{aligned} \theta_{min}^{gROM} &= \bar{\theta}^{aROM} - \gamma \cdot \delta\theta^{aROM} \\ \theta_{max}^{gROM} &= \bar{\theta}^{aROM} + \gamma \cdot \delta\theta^{aROM} \end{aligned} \tag{3}$$

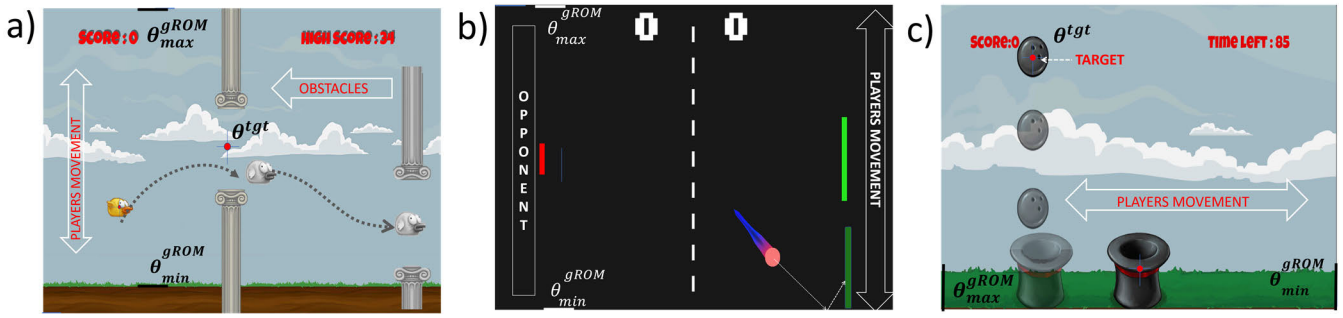

FIGURE 3. Therapy games: a) Flappy-bird game: The player controls the bird's vertical movement and is required to make the bird fly for 90 seconds without crashing into the obstacles. b) Pong Game: The player controls the paddles vertical position and tries to win the rally, and the game difficulty is set by the ball speed and the scaling of the screen size. c) Hat-trick game: This is a classic reaching to target game where the player is required to reach the target before a specific time.

TABLE 3. Game design parameters: The difficulty parameters are changed to match the level set by the GDA. The performance parameter summarizes the movements made in a trial to a binary value (success or failure).

Game	Game objective	Difficulty parameters	Performance parameter (Success)
Flappy Bird	The player controls the bird's vertical position to avoid the obstacles in the flight.	1. Amount of movement required to transverse the screen vertically. 2. Speed of bird	Bird flight for 90 seconds
Ping Pong	Intercept the ball and make the opponent miss the ball.	1. Size of the paddle. 2. Speed of the ball.	Opponent misses the ball.
Hat Trick	The player controls the horizontal position of the hat to catch the falling balls.	1. Amount of movement required to transverse the screen horizontally. 2. Speed of the target falling from the top	No of drops < 4 in a 90-second game trial.

where, $\bar{\theta}^{aROM} = \frac{\theta^{aROM}_{max} + \theta^{aROM}_{min}}{2}$, $\delta\theta^{aROM} = \frac{\theta^{aROM}_{max} - \theta^{aROM}_{min}}{2}$, and $\gamma \in [0.2, 1]$. The value of γ is set to 0.6 for the first time a subject plays a game, and it is subsequently adapted depending on the subject's game performance. When the game is played in the assisted mode, GROM is computed using Eq. 3 with PROM replacing AROM. Game speed (ω_g) determines how fast the subject needs to move to reach targets in the game. There is no upper bound on the speed of movement in these games, and the lower bound was set empirically for all games to be around 10 deg/sec.

The positions for the targets θ^{tgt} presented in a Hat-trick and Flappy-bird game were randomly chosen to ensure patients reach targets close to the limits of his/her current GROM. Targets close to the edges of the interval $\left[\theta^{gROM}_{min}, \theta^{gROM}_{max}\right]$ were sampled with a higher probability than the ones in the center, using the following probability density function,

$$f\left(\theta^{tgt}\right) = \begin{cases} 0.\bar{5}, & \left|\theta^{tgt} - \bar{\theta}^{gROM}\right| \leq 0.6 \cdot \delta\theta^{gROM} \\ 1.\bar{6}, & \text{Otherwise} \end{cases} \quad (4)$$

where, $\bar{\theta}^{gROM} = \frac{\theta^{gROM}_{max} + \theta^{gROM}_{min}}{2}$, $\delta\theta^{gROM} = \frac{\theta^{gROM}_{max} - \theta^{gROM}_{min}}{2}$.

In the current version of PLUTO, the performance parameters were simple measures related to the game objectives, as shown in Table 3. The performance in a game is mapped to a binary value indicating the success or failure of a subject in achieving the game objective.

G. GAME DIFFICULTY ADAPTATION (GDA)

The game difficulty adaptation (GDA) algorithm follows the challenge point framework [52], where the game difficulty is varied on a trial-by-trial basis to match a patient's performance. GROM and game speed (γ, ω_g) determine the game difficulty. Whenever there is a continued success (three consecutive successful game trials), the game difficulty is increased by incrementing both γ and ω_g by 5%. On the other hand, when there is a continued failure (three consecutive failed trials), either γ or ω_g is reduced by 5% randomly with equal probability.

III. SYSTEM CHARACTERIZATION

PLUTO's physical human-robot interaction characteristics were evaluated through a series of experiments to estimate static friction of the actuator and the different mechanisms, step-response, and closed-loop bandwidth of the torque controller, and the robot's backdrivability.

A. INERTIA, DAMPING, AND STATIC FRICTION OF THE MOTOR AND THE MECHANISMS

The details of the experimental procedure used for identifying these parameters are provided in the supplementary material. Static friction in PLUTO is due to the motor-gearbox assembly and the passive mechanisms attached to the robot. It is measured from the minimum motor current required to move the motor with and without the passive mechanisms.

The robot's motor-gearbox assembly has static friction of 0.30 ± 0.37 Nm. The WFE, FPS, and HOC mechanisms have static friction of 0.07 ± 0.02 Nm, 0.17 ± 0.19 Nm, and 0.18 ± 0.21 Nm, respectively. The FPS and HOC have higher static friction than the WFE due to the additional gears used in these mechanisms.

The inertia and viscous damping were identified using a chirp input to the motor. The inertia and damping of the motor-gearhead assembly is 5.44×10^{-3} kg $\cdot$ m^2 and 50.55×10^{-3} Nm $\cdot$ s $\cdot$ rad^{-1}, respectively. The inertia for the WFE, FPS and HOC are 0.66×10^{-3} kg $\cdot$ m^2, 1.25×10^{-3} kg $\cdot$ m^2, and 0.77×10^{-3} kg $\cdot$ m^2, respectively. The viscous damping for WFE, FPS, and HOC are 0.26×10^{-3} Nm $\cdot$ s $\cdot$ rad^{-1}, 3.89×10^{-3} Nm $\cdot$ s $\cdot$ rad^{-1}, and 10.9×10^{-3} Nm $\cdot$ s $\cdot$ rad^{-1}, respectively.

B. TORQUE CONTROLLER PERFORMANCE

The performance of the torque controller depends on the impedance attached to the robot. PLUTO's torque controller was first characterized by locking the motor shaft from rotating, simulating a body with infinite impedance (Fixed condition in Table 4). The characterization was carried out by applying step input of magnitude 1 Nm as the desired torque $\tau_d(t)$ while simultaneously measuring $\tau_a(t)$. The overall closed-loop dynamics of the torque controller was modeled as a second-order linear system with time delay,

$$T_s^2 \ddot{\tau}_a(t) + 2\zeta T_s \dot{\tau}_a(t) + \tau_a(t) = K \cdot \tau_d\left(t - T_p\right) \quad (5)$$

where K is the overall gain of the controller, ζ is the damping factor, T_s is the second-order time constant, and T_p is the dead time. The model parameters were identified using the sequential least squares programming (SLSQP) algorithm in SciPy [53] to minimize the squared differences between the $\tau_a(t)$ and the predicted actual torque by the model for the step input.

Following this, three individual closed-loop torque controller models (same as Eq. 5) were identified for the three mechanisms WFE, FPS, and HOC by attaching a mock setup with human limb-like impedance (refer to the Supplementary Material for the setup details). The inertia for the mock wrist and forearm setup were 3×10^{-3} kg$\cdot$m^2 and 6×10^{-3} kg$\cdot$m^2, respectively [54]; the inertia of the fingers and the thumb were assumed to be negligible. The stiffness of the wrist flexion-extension, forearm, and fingers/thumb was set to 1.2 Nm $\cdot$ rad^{-1}, 0.3 Nm$\cdot$rad^{-1}, and 2 N$\cdot$cm^{-1}, respectively [55], [56]. A step torque input of 1 Nm was applied to these physical models, and the model in Eq. 5 was identified; Table 4 shows the identified parameters for these three models.

In addition to model identification using a step input, we also used a chirp input (Amplitude: 1 Nm, frequency sweep: 0.01 Hz to 10 Hz in 60 seconds) to identify the controller bandwidth. We measured the actual torque from the torque controller with the infinite and simulated human limb impedances. The magnitude spectrum of the closed-loop torque controller was obtained by computing the magnitude of the ratio of average FFT of the actual torque and that of the chirp input. The 3 dB cut-off from the DC gain was used as the definition of the controller bandwidth. Table 3 (last column) also shows the estimated bandwidths for the different conditions.

TABLE 4. Torque controller performance - mean (STD).

	Gain	Time Constant	Damping Factor	Deadtime (s)	Cutoff (Hz)
FIXED	0.83 (0.0015)	0.01 (5.5e-6)	1.03 (0.014)	0.012 (1.3e-4)	7.96
WFE	1.04 (0.07)	0.175 (0.04)	0.75 (0.07)	0.12 (0.04)	1.54
FPS	0.99 (0.10)	0.16 (0.012)	0.79 (0.02)	0.14 (0.05)	1.66
HOC	0.97 (0.09)	0.17 (0.01)	0.77 (0.031)	0.10 (0.04)	1.58

C. BACKDRIVABILITY

PLUTO's backdrivability was evaluated by estimating the impedance of the robot's motor-gearhead assembly with and without the torque controller. A second motor M_o was connected to the robot's output shaft and M_o applied position perturbations $\theta_p(t)$ to the robot's output shaft while measuring the interaction torque $\tau_a(t)$, and velocity $\omega_a(t)$. The impedance of the robot was modeled as a linear first-order system with inertia (I), and damping (B),

$$I\dot{\omega}_a(t) + B\omega_a(t) = \tau_a(t) \quad (6)$$

These parameters were identified through a linear least-squares fitting procedure,

$$\begin{bmatrix} I \\ B \end{bmatrix} = \mathbf{A}^{+} \cdot \boldsymbol{\tau}; \quad \boldsymbol{\tau} = \begin{bmatrix} \tau_a(t_1) \\ \tau_a(t_2) \\ \vdots \\ \tau_a(t_N) \end{bmatrix};$$
$$\mathbf{A} = \begin{bmatrix} \dot{\omega}_a(t_1) & \omega_a(t_1) \\ \dot{\omega}_a(t_2) & \omega_a(t_2) \\ & \vdots \\ \dot{\omega}_a(t_N) & \omega_a(t_N) \end{bmatrix} \quad (7)$$

where N is the total number of data points recorded from the experiment, $\mathbf{A}^{+}$ is the Moore-Penrose pseudoinverse of $\mathbf{A}$. The two parameters I and B were identified with and without the torque controller; when the torque controller was used, the desired torque was set to 0 Nm. Static friction was identified as in Section III (A), but with the motor M_o applying a ramped torque to move the robot's motor-gearhead assembly. The torque controller reduces the perceived inertia and damping and almost fully compensates for the robot motor-gearhead assembly's static friction (Table 5).

IV. CLINICAL TESTING WITH STAKEHOLDERS

As a first step towards clinically evaluating PLUTO, a pilot usability study was conducted. The aim was to evaluate PLUTO's usability for training different hand functions with the stakeholders: patients, caregivers, and clinicians. This

TABLE 5. Backdrivability.

Torque Controller	Inertia (10^{-3} kg · m^2)	Viscous damping (10^{-3} Nm · s · rad^{-1})	Static Friction (Nm)
Enabled	2.3	1.2	0.02
Disabled	7.06	56.5	0.33

study specifically evaluated the: (a) perceived experience by patients and clinicians when using the device as measured by the user experience questionnaire (UEQ) [57], and (b) perceived usability of PLUTO as measured by the system usability scale (SUS). The institutional review board of the Christian Medical College (CMC) Vellore (IRB registration number: 9484 approved June 30th, 2015, CTRI trial reg: CTRI/2019/10/021741) approved this study.

A. STUDY PARTICIPANTS

The study included a convenience sample of 15 patients, 15 caregivers, and 15 clinicians. The patients in the study were recruited from the Occupational Therapy Unit of the Department of Physical Medicine and Rehabilitation (PMR) at CMC Vellore. The inclusion criteria for recruitment were: (a) age between 12 to 70 years with a minimum best-corrected vision of 6/6; (b) patients prescribed for hand rehabilitation following any neurological lesion. Patients were excluded from the study if: (a) they were unwilling or unable to use the system, and (b) if they had a problem with understanding and following instructions. The study's patient population included anyone prescribed hand therapy irrespective of their underlying pathophysiology since PLUTO is a general tool for training and assessing hand functions.

1) STUDY PROTOCOL: PATIENTS AND CAREGIVERS

After obtaining informed consent, patients trained with PLUTO for two 1-hour sessions each on two different days, the first session involved a demonstration of the different features of the robot and its passive mechanisms to the patient and his/her caregiver by the engineer (Author 1) and the therapist (Author 2). The caregiver was the patient's significant relative or the hospital attendant supported during the rehabilitation process and ADL. The demo included the procedure to plug-in and plug-out the passive mechanisms, adjust and fix the armrest and the trolley, use the emergency stop button, and use the software to play the therapy games with the robot.

After the demo, the caregiver helped the patient train using the robot with minimal supervision from the therapist or the engineer. Before starting the training, the treating therapist decided the mechanisms and the training regimes that a patient would use and evaluate as part of the study. After completing the two training sessions, the patient evaluated the system and his/her experience using the SUS and UEQ. The caregiver evaluated the system only using the SUS. An illustration of a wheelchair user training with is the PLUTO is shown in the supplementary file (Fig. 2), and actual patient training is shown in the supplementary video.

2) STUDY PROTOCOL: CLINICIANS

After obtaining informed consent, a demonstration of the robot's features was given to the clinicians with a healthy volunteer using the robot. Different features of the device such as plug-in procedure, passive mechanisms for training different hand functions, ROM assessments, therapy games, therapy regimes, performance adaptive game adaptation, and data logging were first presented; this also included selected videos of some patients using the different mechanisms. Following this, the entire system was demoed with a healthy volunteer using the system. This demo was identical to the one used with patients and caregivers — the healthy volunteer trained with all passive mechanisms in active and active-assist training regimes. Clinicians were also encouraged to test the various features of the robot on the healthy volunteer or on themselves. Following the hands-on demo and evaluation of the various features, clinicians evaluated the system using the SUS and the UEQ. Of the 15 clinicians who participated in the study, four clinicians were given individual demo sessions; the rest were given demo in small groups of 3-4 clinicians.

B. OUTCOME MEASURES

The system usability scale and the user experience questionnaire were the two primary outcome measures of the present study.

1) SYSTEM USABILITY SCALE (SUS)

The SUS [58] is a questionnaire-based assessment tool for capturing the subjective assessment of the usability of a system. The SUS has 10 items, with each scored on a Likert scale between 0 to 4. The final score is scaled by 2.5 to obtain a maximum score of 100. The SUS score is used as the criterion to classify the system as usable. A score of 100 would correspond to the best imaginable usability. A score above 70 corresponds to acceptable or good usability, and a score between 52 and 70 would correspond to marginal usability. A sample size of at least 12 is required to reliably estimate system usability using the SUS [59]. The usability study had an overall sample size of 45, with 15 participants in each group.

2) USER EXPERIENCE QUESTIONNAIRE (UEQ)

The UEQ [57] is often used as part of a classical usability test to collect quantitative data about the participants' experience in using the system. UEQ is also standardized questionnaire using a 7-point Likert scale with 26 questions. The questions in UEQ are grouped into 6 sub-scales evaluating attractiveness, perspicuity, efficiency, dependability, stimulation, and novelty.

1. **Attractiveness:** Describes the user's general impression of the robot. Summarizes if the users liked it or not.
2. **Dependability:** Describes whether the users felt they were in control of the device and if they found it secure and predictable.
3. **Efficiency:** Describes how quickly and efficiently the user could operate the robot. For this study, patients were asked to rate the PC software as well as the hardware.
4. **Perspicuity:** Describes how easily the user could understand the different functions of the robot.
5. **Novelty:** Describes whether the product's design was perceived as innovative, creative, and aroused the users' attention. Since all the subjects were first-time users of a rehabilitation robot, they were asked to compare it to a conventional training experience.
6. **Stimulation:** Describes the user's interest and excitement about the system and their interest to continuously use it.

C. STATISTICAL ANALYSIS

Comparisons of the results across the three groups were performed using one-way ANOVA. A comparison between items of the SUS and UEQ questionnaires across groups was carried out through a two-way ANOVA. All data are presented as mean ± standard deviation. The significance level was set as $p < 0.05$. Guttman's $\lambda 2$ was calculated to measure the reliability of the UEQ questionnaire. One sample t-test was performed to check if the mean SUS score is statistically greater than 70 (acceptable SUS range).

V. RESULTS

The pilot usability study was conducted between January 2020 and August 2020 at the PMR Department at CMC Vellore. Fifteen patients, fifteen caregivers, and fifteen clinicians participated in the study. The patient group consisted of 2 persons with stroke, 4 persons with traumatic brain injury, 1 person with Guillain-Barre syndrome, 5 persons with incomplete spinal cord injury, 2 persons with cerebral palsy, and 1 person with Parkinson's disease. The mean age of the patient group was 36.93 (±14.14) years with 5 females. Among the 15 clinicians recruited for the study, 6 were occupational therapists, 5 were physical therapists, and 4 were physiatrists.

Not all mechanisms and training regimes were used by all patients. All patients used the WFE mechanism, 6 patients used the HOC mechanism, 13 used the FPS mechanism, and only 1 patient used the WURD mechanism. The list of mechanisms, games, and training regimes tested by different patients is provided in Supplementary Table 1. Also, the patient's ROM as assessed by the robot is detailed in Supplementary Table 2.

A. SYSTEM USABILITY SCALE (SUS)

The distribution of responses from patients, caregivers, and clinicians from the SUS is depicted in Fig. 4, where the scores from 0 to 4 are depicted in different colors, with red corresponding to 0 and green to 4; more green indicates a higher positive rating for the system for that question. For the SUS items 1, 3, 5, 7, and 9, a score of zero/red corresponds to total disagreement, and four/green corresponds to total agreement. The reverse is true for items 2, 4, 6, 8, and 10. The sum over all the items is multiplied by 2.5 to get the final score between 0 to 100.

The mean SUS score for the clinicians, caregivers, and patients was 70.5±12.5, 75.2±14.1, and 74.5±17.9, respectively. Out of the total 45 participants, 2 participants (∼4.4%) reported low/poor usability (SUS < 50), and 25 participants (∼55.5%) reported acceptable usability (SUS > 70). The overall mean across the 45 participants was 73.84 indicating acceptable usability ($SUS > 70, t = 1.81, p = 0.038$). Twelve of the 15 patients reported an overall score of 65 and above, with three patients P08, P06, and P15 reporting scores of 63, 60, and 60, respectively. Among the 15 clinicians, the SUS scores had a wide range with a maximum and minimum score of 97.5 and 40.

ANOVA revealed no difference in SUS scores across groups (F score $= 0.421$, $p = 0.65$). Questions 4 and 10 were graded the least by all the groups with a mean score of 1.98 and 2.0, respectively. These questions were specifically focused on evaluating the user's confidence to operate the system independently. On the other hand, the group mean for question 8 was 3.23, indicating the participants were comfortable using the system. This probably means that the participants were comfortable using the system once it was set up, and the main difficulty was setting up the system. The detailed summary of the SUS obtained from patients, caregivers, and clinicians is available in the supplementary material.

B. USER EXPERIENCE QUESTIONNAIRE

In the UEQ, 17 of the 26 questions had a mean score greater than 0.8 by both the patients and the clinicians, suggesting a positive evaluation (Fig. 5). The question ''slow/fast'' (question 17) was the only question rated negatively with a mean score of -0.4 among patients. All other questions had a neutral evaluation. The questions ''likable'' and ''interesting'' had the highest positive scores among patients (mean score of 2.7).

The results from the UEQ show that both patients and clinicians rated the system positively on all six UEQ subscales (Fig. 6); no subscale was scored negatively across groups. Two-way ANOVA revealed no statistical differences between groups (F score $=0.6$, $p=0.42$) and subscales. The attractiveness scale was graded the highest by both the patients (2.3) and the clinicians (2.3). Whereas the novelty was graded the least by both groups. Clinicians had reported reliable results in attractiveness, perspicuity, and efficiency, whereas patients' results were found reliable only in attractiveness and efficiency subscales. The overall reliability (Guttman's $\lambda 2$) was 0.64 and 0.69 among patients and clinicians, respectively.

FIGURE 4. **System usability scale question wise results: The plot gives the distribution of the SUS across patients clinicians and caregivers. The SUS scores of 0 is mapped to red and 4 is mapped to green. For items 1, 3, 5, 7, and 9: a score of zero (red) corresponds to total disagreement and a score of four (green) corresponds to total agreement. The reverse is true for items 2, 4, 6, 8, and 10. Thus, green color in the plots corresponds to positive rating and red corresponds to a negative rating.The sum over all the items is multiplied by 2.5 to get the final score between 0 to 100.**

VI. DISCUSSION

This paper described PLUTO's design and preliminary evaluation, a modular, single DOF robot that can individually train four different hand functions through gamified therapy. This work demonstrates the potential of a single actuator system for addressing the need for training wrist, forearm, and hand functions individually. Some of the key advantages of PLUTO that make it a clinically viable solution are:

1. **Compact and portable structure:** PLUTO is compact, lightweight, and portable making the device suitable for small clinics and even patients' homes.
2. **Extendable functionalities:** The functions trained with PLUTO can easily be extended beyond the four functions presented in this paper by designing appropriate passive mechanisms.
3. **A small bill-of-materials:** The use of a single actuator and minimal instrumentation results in a low

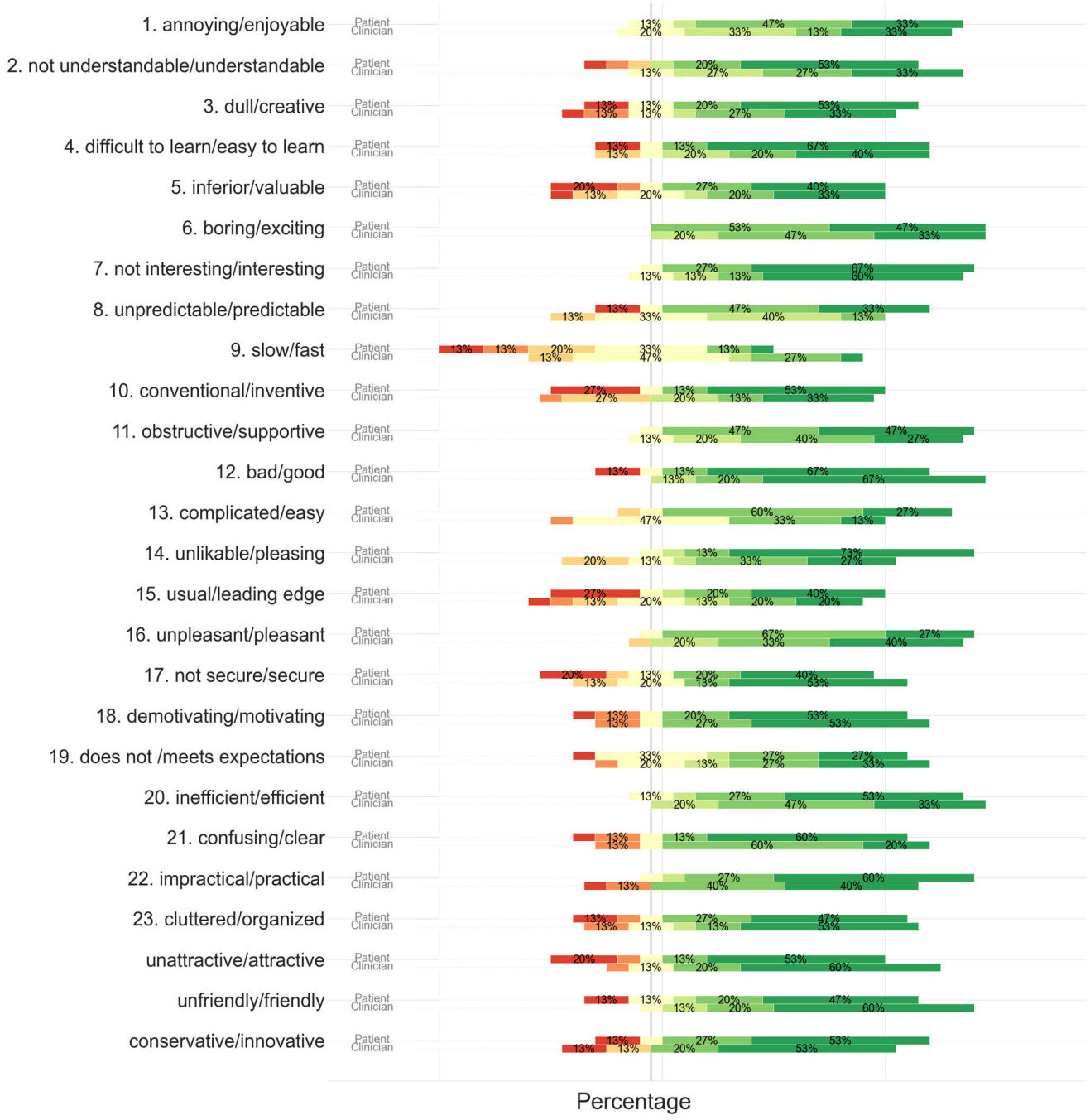

FIGURE 5. **User experience questionnaire question wise results: The plot shows the distribution of responses from the clinicians and the patients. The colors between red and green represent gradations between the opposite attributes. E.g., for the question annoying/enjoyable red corresponds to annoying and green corresponds to enjoyable white corresponds to neutral evaluation.**

bill-of-materials, which can translate into an affordable commercial product.

The pilot usability study suggests that PLUTO generally meets the expectation of patients, caregivers, and clinicians. All subscales in the UEQ were graded positively, and an overall SUS score of 73.3 indicates an acceptable level of system usability. In both scales, the questions pertaining to independent use and learning the technical details were graded low. This is understandable as most participants were first-time users of a robotic system, and their confidence in the independent use of the system is expected to increase with time. Furthermore, PLUTO is still a lab prototype, and thus some of the design features could be sub-optimal for ease of use. Two clinicians raised concerns about the armrest's ergonomics, whose height could not be adjusted for the passive mechanisms. One caregiver reported that plugging the various mechanisms in and out of the robot was difficult, and the same feedback was given by several

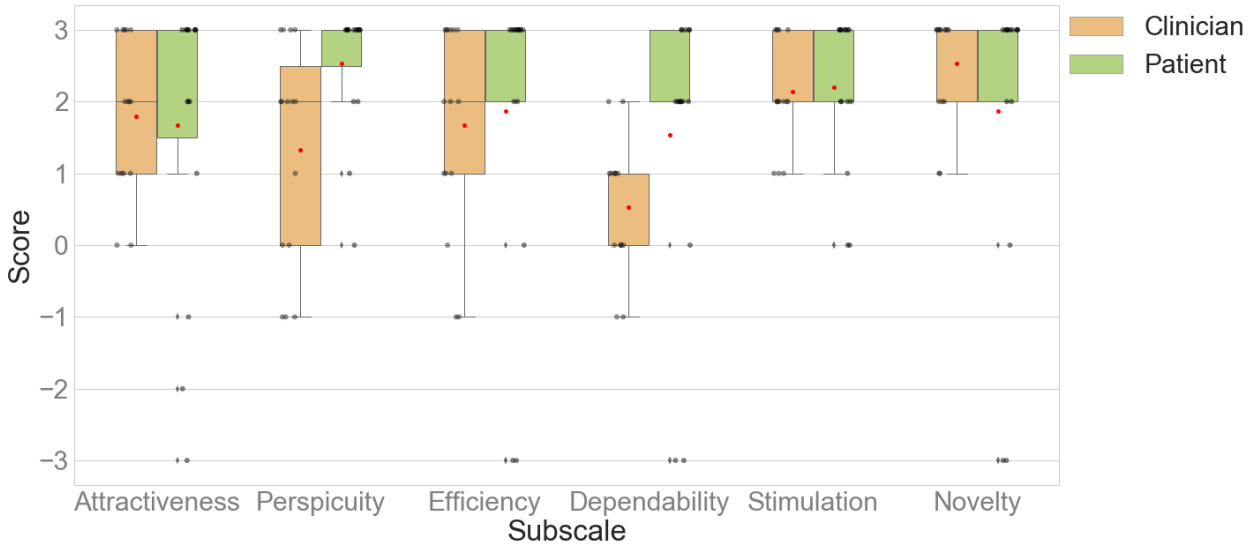

FIGURE 6. User experience questionnaire sub-scale scores. All subscales had a positive score with no difference between the groups. The strip plots show scores of each subject and the red points mark the mean for the respective subscales.

clinicians verbally when filling in the questionnaires; the current plug-in uses a universal hub that requires fastening two bolts to plug in these mechanisms. PLUTO has three performance-adaptive games, two of which can be played with assistance from the robot. Several patients requested more number and variety in the games, which would be essential for long-term usability and therapy. Most patients enjoyed the Pong game the most, probably because the computer opponent presents competitive gameplay. The use of similar games could be beneficial for long-term training with the robot.

The use of a single motor and simple PLUTO mechanisms ensured that the overall inertia and viscous damping of the different mechanisms were quite small. The inertia for the WFE and FPS were almost one-third that of the OpenWrist, which has 3 DOFs [60]. The viscous damping of PLUTO for WFE was comparable to that of OpenWrist, while for FPS, it was almost one-fifth of that of OpenWrist. The static friction of the different mechanisms was comparable among the robots. There were also no issues raised by any of the participants about the physical human-robot interaction with the robot for performing active and assisted movements. PLUTO's good backdrivability ensured by its low inertia, damping, and static friction enabled patients to train actively without significant impedance from the robot. It should be noted that none of the patients tested in the study had severe wrist/hand impairments.

We finally point out some of the limitations of the current design of the robot and the clinical study presented in this paper:

1. These useful features are attained at the expense of the robot's ability to train multiple DOFs simultaneously. However, this design choice might not limit the therapeutic efficacy of PLUTO compared to a multi-DOF robot capable of training multiple functions simultaneously. Firstly, there is some evidence from robot-assisted arm training, which indicates that individual training of the joints can be as effective as coordinated multi-joint training [61]. Fluet *et al.* showed that training the arm and hand together in a coordinated manner has similar effects on recovery as training them separately 62]. Furthermore, the patients requiring robot-assisted therapy are likely to be in the severe-to-moderate end of the impairment spectrum; multi-DOF training might not be a priority for these patients. Thus, from a clinical perspective, PLUTO is an affordable, feature-rich solution to the hand neurorehabilitation problem that is likely to be as effective as training with a complex multi-DOF robot.
2. The universal hub used for plugging the passive mechanisms to the robot must be replaced by a simpler and faster approach that does not require any additional tools for attaching/detaching the passive mechanisms. It would be ideal if a patient could change mechanisms by themselves with their less affected upper limb.
3. The current prototype has passive mechanisms to only train four essential wrist/hand functions. However, the modularity of the design makes it possible to train various other functions (e.g., different types of grasps, finger/thumb training, etc.) through the design of appropriate additional mechanisms.
4. The positive results observed from the short two-session clinical study cannot be used to conclude long-term usability and therapy compliance with the robot. We plan to address this issue through a two-week in-clinic hand therapy study with the robot to evaluate the feasibility of implementing independent therapy with the robot for patients requiring hand neurorehabilitation.

5. The current work has not explored the assessment of wrist and hand function with the robot, which would be essential to maximize the robot's capabilities.

VII. CONCLUSION

The paper presents a modular single DOF robotic system – PLUTO – for individual-assisted training of various wrist/hand functions achieved through a single actuator and a set of passive mechanisms. The current PLUTO version uses four passive mechanisms to train four wrist/hand functions in active and assisted modes. Three performance adaptive games were developed to gamify the training with the robot. A pilot usability study with the different stakeholders indicates that the system has good short-term usability. Future studies are essential to evaluate long-term (≥ 2 weeks) system usability, the feasibility of implementing minimally supervised therapy, and the system's efficacy. We firmly believe that with additional passive mechanisms, assessment features, and improved ergonomics, PLUTO will be a versatile, affordable, and useful system for routine use in clinics and patients' homes for delivering minimally supervised hand therapy.

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DECLARATION OF INTERESTS

The authors declare that they have no competing interests.

REFERENCES

[1] P. B. Gorelick, "The global burden of stroke: Persistent and disabling," *Lancet Neurol.*, vol. 18, no. 5, pp. 417–418, 2019.

[2] E. S. Lawrence, C. Coshall, R. Dundas, J. Stewart, A. G. Rudd, R. Howard, and C. D. A. Wolfe, "Estimates of the prevalence of acute stroke impairments and disability in a multiethnic population," *Stroke*, vol. 32, no. 6, pp. 1279–1284, 2001.

[3] M. Wyndaele and J.-J. Wyndaele, "Incidence, prevalence and epidemiology of spinal cord injury: What learns a worldwide literature survey?" *Spinal Cord*, vol. 44, no. 9, pp. 523–529, Sep. 2006.

[4] K. D. Anderson, "Targeting recovery: Priorities of the spinal cord-injured population," *J. Neurotrauma*, vol. 21, no. 10, pp. 1371–1383, Oct. 2004.

[5] M. Oskoui, F. Coutinho, J. Dykeman, N. Jette, and T. Pringsheim, "An update on the prevalence of cerebral palsy: A systematic review and meta-analysis," *Develop. Med. Child Neurol.*, vol. 55, no. 6, pp. 509–519, 2013.

[6] E. Fedrizzi, E. Pagliano, and E. Andreucci, "Hand function in children with hemiplegic cerebral palsy: Prospective follow-up and functional outcome in adolescence," *Develop. Med. Child Neurol.*, vol. 45, no. 2, pp. 85–91, Feb. 2007.

[7] J. Allington, S. J. Spencer, J. Klein, M. Buell, D. J. Reinkensmeyer, and J. Bobrow, "Supinator extender (SUE): A pneumatically actuated robot for forearm/wrist rehabilitation after stroke," in *Proc. Annu. Int. Conf. IEEE Eng. Med. Biol. Soc.*, Aug. 2011, pp. 1579–1582.

[8] N. Singh, M. Saini, S. Anand, N. Kumar, M. V. P. Srivastava, and A. Mehndiratta, "Robotic exoskeleton for wrist and fingers joint in post-stroke neuro-rehabilitation for low-resource settings," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 27, no. 12, pp. 2369–2377, Dec. 2019.

[9] D. Xu, M. Zhang, H. Xu, J. Fu, X. Li, and S. Q. Xie, "Interactive compliance control of a wrist rehabilitation device (WReD) with enhanced training safety," *J. Healthcare Eng.*, vol. 2019, pp. 1–10, Feb. 2019.

[10] H. S. Nam, N. Hong, M. Cho, C. Lee, H. G. Seo, and S. Kim, "Vision-assisted interactive human-in-the-loop distal upper limb rehabilitation robot and its clinical usability test," *Appl. Sci.*, vol. 9, no. 15, p. 3106, Aug. 2019.

[11] O. Lambercy, L. Dovat, R. Gassert, E. Burdet, C. L. Teo, and T. Milner, "A haptic knob for rehabilitation of hand function," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 15, no. 3, pp. 356–366, Sep. 2007.

[12] T. Higuma, K. Kiguchi, and J. Arata, "Low-profile two-degree-of-freedom wrist exoskeleton device using multiple spring blades," *IEEE Robot. Autom. Lett.*, vol. 3, no. 1, pp. 305–311, Jan. 2018.

[13] C. N. Schabowsky, S. B. Godfrey, R. J. Holley, and P. S. Lum, "Development and pilot testing of HEXORR: Hand EXOskeleton rehabilitation robot," *J. Neuroeng. Rehabil.*, vol. 7, no. 1, p. 36, Dec. 2010.

[14] I. B. Aabdallah, Y. Bouteraa, and C. Rekik, "Design of smart robot for wrist rehabilitation," *Int. J. Smart Sens. Intell. Syst.*, vol. 9, no. 2, pp. 1029–1053, 2016.

[15] X. Zhou, A. Mont, and S. Adamovich, "Evaluation of a 1-DOF hand exoskeleton for neuromuscular rehabilitation," *Lect. Notes Comput. Vis. Biomech.*, vol. 36, pp. 384–397, Feb. 2020.

[16] S. Hesse, G. Schulte-Tigges, M. Konrad, A. Bardeleben, and C. Werner, "Robot-assisted arm trainer for the passive and active practice of bilateral forearm and wrist movements in hemiparetic subjects," *Arch. Phys. Med. Rehabil.*, vol. 84, no. 2, pp. 915–920, 2003.

[17] E. B. Brokaw, I. Black, R. J. Holley, and P. S. Lum, "Hand spring operated movement enhancer (HandSOME): A portable, passive hand exoskeleton for stroke rehabilitation," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 19, no. 4, pp. 391–399, Aug. 2011.

[18] L. Cappello, N. Elangovan, S. Contu, S. Khosravani, J. Konczak, and L. Masia, "Robot-aided assessment of wrist proprioception," *Frontiers Hum. Neurosci.*, vol. 9, pp. 1–8, Apr. 2015.

[19] N. Omarkulov, K. Telegenov, M. Zeinullin, I. Tursynbek, and A. Shintemirov, "Preliminary mechanical design of NU-wrist: A 3-DOF self-aligning wrist rehabilitation robot," in *Proc. 6th IEEE Int. Conf. Biomed. Robot. Biomechatronics (BioRob)*, Jun. 2016, pp. 962–967.

[20] J. A. French, C. G. Rose, and M. K. O'Malley, "System characterization of MAHI Exo-II: A robotic exoskeleton for upper extremity rehabilitation," in *Proc. ASME Dyn. Syst. Control Conf. (DSCC)*, vol. 3, 2014.

[21] M. Atlihan, E. Akdogan, and M. S. Arslan, "Development of a therapeutic exercise robot for wrist and forearm rehabilitation," in *Proc. 19th Int. Conf. Methods Models Automat. Robot. (MMAR)*, Sep. 2014, pp. 52–57.

[22] K. Y. Tong, S. K. Ho, P. M. K. Pang, X. L. Hu, W. K. Tam, K. L. Fung, X. J. Wei, P. N. Chen, and M. Chen, "An intention driven hand functions task training robotic system," in *Proc. Annu. Int. Conf. IEEE Eng. Med. Biol.*, Aug. 2010, pp. 3406–3409.

[23] S. Ueki, H. Kawasaki, S. Ito, Y. Nishimoto, M. Abe, T. Aoki, Y. Ishigure, T. Ojika, and T. Mouri, "Development of a hand-assist robot with multi-degrees-of-freedom for rehabilitation therapy," *IEEE/ASME Trans. Mechatronics*, vol. 17, no. 1, pp. 136–146, Feb. 2012.

[24] *AMADEO*, Tyromotion, Graz, Austria, 2021.

[25] S. W. O'Driscoll and N. J. Giori, "Continuous passive motion (CPM): Theory and principles of clinical application," *J. Rehabil. Res. Develop.*, vol. 37, no. 2, pp. 179–188, 2000.

[26] S. Chiyohara, J.-I. Furukawa, T. Noda, J. Morimoto, and H. Imamizu, "Passive training with upper extremity exoskeleton robot affects proprioceptive acuity and performance of motor learning," *Sci. Rep.*, vol. 10, no. 1, pp. 1–10, Dec. 2020.

[27] T. J. Kimberley, S. Samargia, L. G. Moore, J. K. Shakya, and C. E. Lang, "Comparison of amounts and types of practice during rehabilitation for traumatic brain injury and stroke," *J. Rehabil. Res. Develop.*, vol. 47, no. 9, pp. 851–862, 2010.

[28] N. Takeuchi and S.-I. Izumi, "Combinations of stroke neurorehabilitation to facilitate motor recovery: Perspectives on Hebbian plasticity and homeostatic metaplasticity," *Frontiers Hum. Neurosci.*, vol. 9, p. 349, Jun. 2015.

[29] B. B. Gambassi, H. J. Coelho-Junior, P. A. Schwingel, F. D. J. F. Almeida, T. M. G. Novais, P. D. L. L. Oliveira, B. A. Sauaia, C. D. Melo, M. C. Uchida, and B. Rodrigues, "Resistance training and stroke: A critical analysis of different training programs," *Stroke Res. Treatment*, vol. 2017, pp. 1–11, Dec. 2017.

[30] F. Khan, J. Pallant, B. Amatya, L. Ng, A. Gorelik, and C. Brand, "Outcomes of high- and low-intensity rehabilitation programme for persons in chronic phase after guillain-Barré syndrome: A randomized controlled trial," *J. Rehabil. Med.*, vol. 43, no. 7, pp. 638–646, 2011.
[31] N. S. Ward, F. Brander, and K. Kelly, "Intensive upper limb neurorehabilitation in chronic stroke: Outcomes from the queen square programme," *J. Neurol., Neurosurg. Psychiatry*, vol. 90, no. 5, pp. 498–506, May 2019.
[32] M.-H. Hu, S.-S. Hsu, P.-K. Yip, J.-S. Jeng, and Y.-H. Wang, "Early and intensive rehabilitation predicts good functional outcomes in patients admitted to the stroke intensive care unit," *Disability Rehabil.*, vol. 32, no. 15, pp. 1251–1259, Jan. 2010.
[33] D. Ferrazzoli, P. Ortelli, I. Zivi, V. Cian, E. Urso, M. F. Ghilardi, R. Maestri, and G. Frazzitta, "Efficacy of intensive multidisciplinary rehabilitation in Parkinson's disease: A randomised controlled study," *J. Neurol., Neurosurg. Psychiatry*, vol. 89, no. 8, pp. 828–835, Aug. 2018.
[34] D. Zbogar, J. J. Eng, W. C. Miller, A. V. Krassioukov, and M. C. Verrier, "Movement repetitions in physical and occupational therapy during spinal cord injury rehabilitation," *Spinal Cord*, vol. 55, no. 2, pp. 172–179, Feb. 2017.
[35] N. A. M. Nordin, N. A. A. Aziz, A. F. A. Aziz, D. K. A. Singh, N. A. O. Othman, S. Sulong, and S. M. Aljunid, "Exploring views on long term rehabilitation for people with stroke in a developing country: Findings from focus group discussions," *BMC Health Services Res.*, vol. 14, no. 1, pp. 1–10, Dec. 2014.
[36] G. Turchetti, N. Vitiello, L. Trieste, S. Romiti, E. Geisler, and S. Micera, "Why effectiveness of robot-mediated neurorehabilitation does not necessarily influence its adoption," *IEEE Rev. Biomed. Eng.*, vol. 7, pp. 143–153, 2014.
[37] D. M. Peters, A. K. McPherson, B. Fletcher, B. A. McClenaghan, and S. L. Fritz, "Counting repetitions: An observational study of video game play in people with chronic poststroke hemiparesis," *J. Neurol. Phys. Therapy*, vol. 37, no. 3, pp. 105–111, 2013.
[38] M. Haghshenas-Jaryani, W. Carrigan, C. Nothnagle, and M. B. J. Wijesundara, "Sensorized soft robotic glove for continuous passive motion therapy," in *Proc. 6th IEEE Int. Conf. Biomed. Robot. Biomechatronics (BioRob)*, Jun. 2016, pp. 815–820.
[39] M. Haghshenas-Jaryani, W. Carrigan, and M. B. J. Wijesundara, "Design and development of a novel soft-and-rigid hybrid actuator system for robotic applications," in *Proc. ASME Int. Design Eng. Tech. Conf. Comput. Inf. Eng. Conf., 39th Mech. Robot. Conf.*, vol. 5A. Boston, MA, USA: ASME, Aug. 2015, Art. no. V05AT08A047, doi: 10.1115/DETC2015-47761.
[40] M. C. H. Chua, L. J. Hoon, and R. C. H. Yeow, "Design and evaluation of rheumatoid arthritis rehabilitative device (RARD) for laterally bent fingers," in *Proc. 6th IEEE Int. Conf. Biomed. Robot. Biomechatronics (BioRob)*, Jun. 2016, pp. 839–843.
[41] M. Haghshenas-Jaryani, C. Nothnagle, R. M. Patterson, N. Bugnariu, and M. B. J. Wijesundara, "Soft robotic rehabilitation exoskeleton (REHAB Glove) for hand therapy," in *Proc. ASME Int. Design Eng. Tech. Conf. Comput. Inf. Eng. Conf., 19th Int. Conf. Adv. Vehicle Technol., 14th Int. Conf. Design Educ., 10th Frontiers Biomed. Devices*, vol. 3. Cleveland, OH, USA: ASME, Aug. 2017, Art. no. V003T13A005, doi: 10.1115/DETC2017-68291.
[42] A. A. Reymundo, E. M. Munoz, M. Navarro, E. Vela, and H. I. Krebs, "Hand rehabilitation using soft-robotics," in *Proc. 6th IEEE Int. Conf. Biomed. Robot. Biomechatronics (BioRob)*, Jun. 2016, pp. 698–703.
[43] A. S. Camp, E. M. Chapman, and P. J. Cienfuegos, "Modeling and analysis of hydraulic piston actuation of McKibben fluidic artificial muscles for hand rehabilitation," *Int. J. Robot. Res.*, vol. 40, no. 1, pp. 136–147, 2021, doi: 10.1177/0278364919872251.
[44] A. Yurkewich, I. J. Kozak, D. Hebert, R. H. Wang, and A. Mihailidis, "Hand extension robot orthosis (HERO) grip glove: Enabling independence amongst persons with severe hand impairments after stroke," *J. Neuroeng. Rehabil.*, vol. 17, no. 1, p. 33, Dec. 2020.
[45] K. X. Khor, P. J. H. Chin, A. R. Hisyam, C. F. Yeong, A. L. T. Narayanan, and E. L. M. Su, "Development of CR2-haptic: A compact and portable rehabilitation robot for wrist and forearm training," in *Proc. IEEE Conf. Biomed. Eng. Sci. (IECBES)*, Dec. 2014, pp. 424–429.
[46] Y. Matsui, R. Fujita, A. Harada, T. Sakurai, T. Nemoto, N. Noda, and K. Toba, "Association of grip strength and related indices with independence of activities of daily living in older adults, investigated by a newly-developed grip strength measuring device," *Geriatrics Gerontol. Int.*, vol. 14, pp. 77–86, Apr. 2014.
[47] B. Gopinath, A. Kifley, G. Liew, and P. Mitchell, "Handgrip strength and its association with functional independence, depressive symptoms and quality of life in older adults," *Maturitas*, vol. 106, pp. 92–94, Dec. 2017.
[48] A. Nehrujee, H. Andrew, Reetajanetsurekha, A. Patricia, S. Samuelkamaleshkumar, H. Prakash, S. Srinivasan, and S. Balasubramanian, "A plug- and-train robotic kit (PLUTO) for hand rehabilitation: Pilot usability study," in *Proc. 8th IEEE RAS/EMBS Int. Conf. Biomed. Robot. Biomechatronics (BioRob)*, Nov. 2020, pp. 100–105.
[49] J. Ryu, W. P. Cooney, L. J. Askew, K.-N. An, and E. Y. S. Chao, "Functional ranges of motion of the wrist joint," *J. Hand Surg.*, vol. 16, no. 3, pp. 409–419, May 1991.
[50] J. Rosen, J. C. Perry, N. Manning, S. Burns, and B. Hannaford, "The human arm kinematics and dynamics during daily activities–toward a 7 DOF upper limb powered exoskeleton," in *Proc. 12th Int. Conf. Adv. Robot. (ICAR)*, Jul. 2005, pp. 532–539.
[51] J. M. Soucie, C. Wang, A. Forsyth, S. Funk, M. Denny, K. E. Roach, and D. Boone, "Range of motion measurements: Reference values and a database for comparison studies," *Haemophilia*, vol. 17, no. 3, pp. 500–507, 2011.
[52] M. A. Guadagnoli and T. D. Lee, "Challenge point: A framework for conceptualizing the effects of various practice conditions in motor learning," *J. Motor Behav.*, vol. 36, no. 2, pp. 212–224, 2004.
[53] P. Virtanen, R. Gommers, T. E. Oliphant, M. Haberland, T. Reddy, D. Cournapeau, E. Burovski, P. Peterson, W. Weckesser, J. Bright, and S. J. Van Der Walt, "SciPy 1.0: Fundamental algorithms for scientific computing in Python," *Nature Methods*, vol. 17, pp. 261–272, Feb. 2020.
[54] G. A. Jackson, "Survey of EMC measurement techniques," *Electron. Commun. Eng. J.*, vol. 1, no. 2, pp. 61–70, Mar. 1989.
[55] D. Formica, S. K. Charles, L. Zollo, E. Guglielmelli, N. Hogan, and H. I. Krebs, "The passive stiffness of the wrist and forearm," *J. Neurophysiol.*, vol. 108, no. 4, pp. 1158–1166, Aug. 2012.
[56] P.-H. Kuo and A. D. Deshpande, "Muscle-tendon units provide limited contributions to the passive stiffness of the index finger metacarpophalangeal joint," *J. Biomech.*, vol. 45, no. 15, pp. 2531–2538, Oct. 2012.
[57] M. Schrepp, A. Hinderks, and J. Thomaschewski, "Construction of a benchmark for the user experience questionnaire (UEQ)," *Int. J. Interact. Multimedia Artif. Intell.*, vol. 4, no. 4, p. 40, 2017.
[58] J. Brooke, "SUS-A quick and dirty usability scale," *Usability Eval. Ind.*, vol. 189, no. 194, pp. 4–7, 1996.
[59] J. R. Lewis and J. Sauro, "The factor structure of the system usability scale," in *Proc. Int. Conf. Hum. Centered Design*. Berlin, Germany: Springer, 2009, pp. 94–103.
[60] E. Pezent, C. G. Rose, A. D. Deshpande, and M. K. O'Malley, "Design and characterization of the OpenWrist: A robotic wrist exoskeleton for coordinated hand-wrist rehabilitation," in *Proc. Int. Conf. Rehabil. Robot. (ICORR)*, Jul. 2017, pp. 720–725.
[61] J. Kein, S. J. Spencer, and D. J. Reinkensmeyer, "Breaking it down is better: Haptic decomposition of complex movements aids in robot-assisted motor learning," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 20, no. 3, pp. 268–275, May 2012.
[62] G. G. Fluet, A. S. Merians, Q. Qiu, A. Davidow, and S. V. Adamovich, "Comparing integrated training of the hand and arm with isolated training of the same effectors in persons with stroke using haptically rendered virtual environments, a randomized clinical trial," *J. Neuroeng. Rehabil.*, vol. 11, no. 1, p. 126, 2014.

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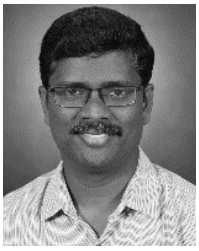

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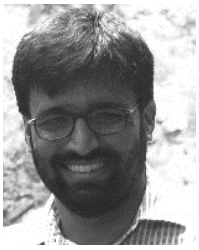

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