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

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Abstract — **Hand neurorehabilitation involves the training of movements at various joints of the forearm, wrist, fingers, and thumb. Assisted training of all these joints either requires either one complex multiple degree-of-freedom (DOF) robot or a set of simple robots with one or two DOF. Both of these are not economically or clinically viable solutions. The paper presents work that addresses this problem with a single DOF robot that can train multiple joints one at a time – the plug and train robot (PLUTO). 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-closings. 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 toward clinical validation, the device's usability was evaluated in 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. Clinicians, on the other hand, had a single session demo after which feedback was obtained. The total SUS score obtained from the patients, clinicians, and healthy subjects was 73.3 ± 14.6 (n = 45), indicating good usability. The UEQ score was rated positively in all subscales by both the 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 indicates that with additional passive mechanisms, assessment features, and optimized ergonomics, PLUTO will be a versatile, affordable, and useful system for routine use in clinics and also patients' homes for delivering minimally supervised hand therapy.**

Index Terms— **Hand rehabilitation; rehabilitation robot; usability;**

I. Introduction

Impairments of hand function can significantly affect simple activities of daily living (ADL) tasks such as feeding, self-care, etc., and have a debilitating effect on a person's quality of life. Hand impairments are commonly observed in neurological disorders such as stroke, spinal cord injury, etc.

In stroke patients, recent studies have shown that targeted high-intensity training can reduce impairments and increase functional activity even in the chronic stage [1], [2]. These results are in line with the animal studies by Nudo et al. in stroke models; monkeys performed 600 repetitions of a pellet retrieval task per day which helped reverse the impairments due to a cortical lesion [3], [4]. However, in stark contrast to these observations, 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 [5]. Several factors are responsible for this state of affairs: growing patient population [6], high patient to therapist ratio (as high 25000:1 [7]), limited healthcare budget [8], etc.

Rehabilitation robots can address some of these problems by providing intense, semi-automated therapy with intermittent, direct/remote supervision from a therapist. When combined with computer games, they make intense therapy more exciting and engaging for patients [9]. In the last few decades, various hand rehabilitation robots ranging from simple single joint robots to complex multi-joint exoskeletons have been developed and evaluated. A systematic review in 2010 found 30 devices capable of training hand rehabilitation [10], and in just six years, by 2016, the number of designs published has increased to 165 [11]. However, the penetration of rehabilitation robots into clinical practice has been limited [12]. One of the primary reasons for this is the affordability of existing rehabilitation robots [13], [14]; most existing devices are prohibitively expensive for the number of features they offer.

Rehabilitation of hand functions requires patients to train various joints, including the wrist, forearm, fingers, thumb, etc. Assisted training of these various joints can be achieved through the use of several simple (1 or 2 degrees-of-freedom (DOF)) robots [15]–[17] that can only train one or two specific movements, or a complex multi-DOF (more than 2 DOF) robot [18]–[20] capable of training various functions individually or simultaneously. Both solutions are not economically viable and are likely to have low clinical adoption.

One possible solution to this problem is a simple, compact, single DOF robot capable of training multiple joint movements. Such a solution can be achieved through a single actuator to which a set of passive mechanisms can be easily attached/detached, with each passive mechanism designed to

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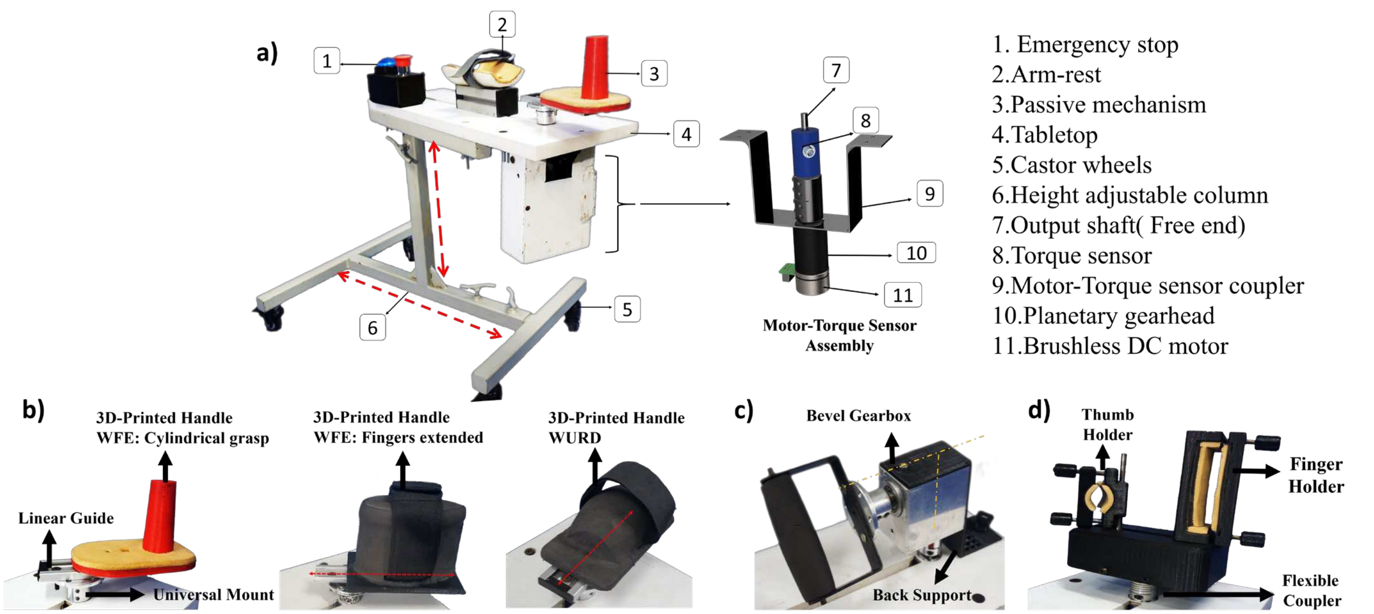


Fig. 1. PLUTO Design a) PLUTO height adjustable trolley setup and motor torque-sensor assembly b) Wrist mechanism: Wrist Flexion-Extension and Wrist Ulnar-Radial Deviation (WFE and WURD) c) Pronation-Supination(FPS) mechanism d) Hand opening-closing (HOC) mechanism

TABLE I
DEVICE CAPABILITIES COMPARED WITH REQUIREMENTS FOR ADL [35], [36], THE BIOMECHANICAL LIMITS IN HEALTHY [37]

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

train a particular joint movement or function. The goal of the current project was to develop and evaluate such a robot, which we refer to as the Plug and Train Robot (PLUTO). Although such a design would preclude the possibility of training multiple DOF simultaneously (e.g. hand grasp while performing forearm pronation/supination), this may not be a major issue for two reasons: (a) multi-DOF movement are unlikely to be the primary focus for moderate and severely affected patients requiring assisted therapy using a robot, and (b) there is currently no evidence favoring multi-DOF training over single DOF training; there is, however, some evidence showing that training individual DOFs is as effective as training multiple DOFs simultaneously [21]. Khor et al. recently presented a hand rehabilitation robot with a similar design approach as PLUTO – CR2-Haptic [22], which uses a single actuator and changeable handles to train wrist/forearm functions. The proposed design for PLUTO overcomes the short-comings of the CR2-Haptic: (a) 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), and (b) CR2-Haptic does not support hand-opening and closing movements.

In this paper, we present 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 [23].

II. PLUTO Architecture

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

1. Wrist flexion/extension (WFE)
2. Wrist ulnar/radial deviation (WURD)
3. Forearm pronation/supination (FPS)
4. Gross hand opening and closing (HOC)

Table I summarizes the recommended force/torques and range of motion (ROM) for the four different wrist/hand functions, along with the corresponding capabilities of PLUTO. The robot is mounted on a portable setup with provisions to adjust the tabletop's height to accommodate different wheelchairs and beds.

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 of 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 rotation by 90 degrees; the flexible couplers account for small misalignments between the robot and the human joint axes [24].

The HOC mechanism converts the actuator's rotary motion into a translational motion using a rack-and-pinion mechanism (pitch diameter 60 mm, module 1). A single pinion mates with two racks placed at diametrically opposite sides of the pinion, 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 a back-support to prevent them 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 3.5Nm at 350 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. 1A). A metal enclosure with dimensions $15 \times 7 \times 10$ 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, 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:

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

where t is time, $\tau_d(t)$ is the desired interaction torque, k_p is the controller gain, 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 $\omega_d(t) = 0$ 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 was not implemented.

Assist-as-needed (AAN) controller: The AAN controller [23] minimally assist a patient in reaching targets outside his/her active range of motion (AROM). This is implemented on top of the torque controller through a simple rule that learns a user-specific map $\left(\tau^{tgt} = \mathrm{T}_{AAN}(\theta^{tgt})\right)$ between target locations θ^{tgt} and the assistance torque τ^{tgt} required to reach these targets. On a given movement trial (e.g., trial number k) of duration Tsec, when the target location θ^{tgt} is presented to a subject to reach, the assistance torque corresponding to this target is applied to the subject in a smooth fashion using a sigmoid function.

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

The AAN algorithm updates the assistance $\mathrm{T}_{AAN}(\theta^{tgt})$ 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 [23].

D. 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, following which 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.

E. Therapy games

To reduce the boredom of repetitive exercises, training with PLUTO was gamified with three performance adaptive games (Fig. 2). 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 difficulty levels of the games were determined by the magnitude and the speed of movements required to play these games which are controlled by their difficulty parameters (Table II).

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 $\left(\omega_g\right)$ parameters, respectively. GROM sets the limits of the movements required from a subject to transverse 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

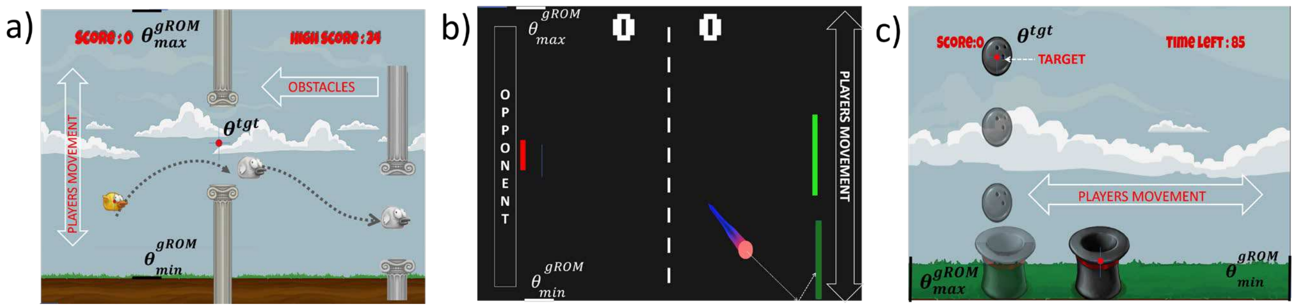


Fig. 2. Therapy games : a) Flappy-bird game: The player controls the bird's vertical movement and is required to make the bird fly for 90 seconds without crashing into the obstacles. b) Pong Game: The player controls the paddles vertical position and tries to win the rally, and the game difficulty is 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 II
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)
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.
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.

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 (θ_{min}^{aROM}) and maximum (θ_{max}^{aROM}) 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 $\left(\theta_{max}^{gROM}\right)$ robot joint angles that can be safely reached by the subject when his/her limb is moved passively by the robot. When a game is played under the active mode,

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

where, $\bar{\theta}^{aROM} = \frac{\theta_{max}^{aROM}+\theta_{min}^{aROM}}{2}$, $\delta\theta^{aROM} = \frac{\theta_{max}^{aROM}-\theta_{min}^{aROM}}{2}$, and $\gamma \in [0, 1]$. The value of α 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, the GROM is computed with Eq. 3 but using PROM instead of AROM. The GROM is parametrized by γ. Game speed $\left(\omega_g\right)$ determines how fast a 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 $\left[\theta_{min}^{gROM}, \theta_{max}^{gROM}\right]$ 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, $\bar{\theta}^{gROM} = \frac{\theta_{max}^{gROM}+\theta_{min}^{gROM}}{2}$, $\delta\theta^{gROM} = \frac{\theta_{max}^{gROM}-\theta_{min}^{gROM}}{2}$.

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

Game Difficulty Adaptation (GDA): The game difficulty adaptation (GDA) algorithm follows the challenge point framework [25], where the game difficulty is varied on a trial-by-trial basis to match a patient's performance. The game difficulty, determined by GROM and game speed $\left(\gamma, \omega_g\right)$. 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 (randomly with equal probability) γ or ω_g is reduced by 5%.

III. SYSTEM CHARACTERIZATION

The characteristics of PLUTO's physical human-robot interaction 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 a 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 $5.44 \times 10^{-3}\ \mathrm{kg \cdot m^2}$ and $50.55 \times 10^{-3}\ \mathrm{Nm \cdot rad^{-1}}$, respectively. The inertia for the WFE, FPS, and HOC are $0.66 \times 10^{-3}\ \mathrm{kg \cdot m^2}$, $1.25 \times 10^{-3}\ \mathrm{kg \cdot m^2}$, and $0.77 \times 10^{-3}\ \mathrm{kg \cdot m^2}$, respectively. The viscous damping for WFE, FPS, and HOC are $0.26 \times 10^{-3}\ \mathrm{Nm \cdot rad^{-1}}$, $3.89 \times 10^{-3}\ \mathrm{Nm \cdot rad^{-1}}$, and $10.9 \times 10^{-3}\ \mathrm{Nm \cdot rad^{-1}}$, 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 IV). 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,

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

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 [26] 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 set-up with human limb like impedance (refer to the Supplementary Material for the setup details). The inertia for the mock wrist and forearm setup were $3 \times 10^{-3}\ \mathrm{kg \cdot m^2}$ and $6 \times 10^{-3}\ \mathrm{kg \cdot m^2}$, respectively [27]; 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 $1.2\ \mathrm{Nm \cdot rad^{-1}}$, $0.3\ \mathrm{Nm \cdot rad^{-1}}$, and $2\ \mathrm{N \cdot cm^{-1}}$, respectively [28], [29]. A step torque input of 1 Nm was applied to these physical models, and the model in Eq. 5 was identified; Table IV shows the identified parameters for these three models.

TABLE IV
TORQUE CONTROLLER PERFORMANCE - MEAN (STD)

	Gain	Time Constant	Damping Factor	Deadtime (s)	Cutoff (Hz)
FIXED	0.83 (.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

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). 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 measured 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 IV (last column) also shows the estimated bandwidths for the different conditions.

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 $\tau_a(t)$, robot position $\theta_a(t)$, and velocity $\omega_a(t)$. The impedance of the robot was modeled as a linear first-order system with inertia (I), and damping (B),

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

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

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

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 the 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's motor-gearhead assemblies static friction (Table V).

IV. PILOT CLINICAL TESTING WITH STAKEHOLDERS

As a first step towards clinically evaluating PLUTO, a pilot usability study was conducted. The aim was to evaluate

TABLE V
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

PLUTO's usability for training different hand functions with the different stakeholders: patients, caregivers, and clinicians. This study specifically evaluated the: (a) perceived experience by patients and clinicians when using the device as measured by the user experience questionnaire (UEQ) [30], and (b) perceived usability of PLUTO as measured by the system usability scale (SUS) [31].

A. Study Participants

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. 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 18 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.

B. 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 had a demonstration of the different features of the robot and its passive mechanisms to the patient and his/her caregiver by the engineer (AN) or the therapist (HA). The caregiver was the patient's significant relative or the hospital attendant who provided support during the rehabilitation process and ADL.

Following the demo, the caregiver helped the patient train with the robot with minimal supervision from the therapist or the engineer. 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.

C. Study Protocol: Clinicians

After obtaining informed consent, a demonstration of the robot's features was given to the clinicians with a healthy subject using the robot. Clinicians were encouraged to test the various features of the robot on a healthy subject or 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 with 3-4 clinicians.

D. 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 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, and the 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 72 corresponds to acceptable or good usability, and a score between 52 and 70 would correspond to marginal usability [32]. A sample size of at least 12 is required to reliably estimate system usability using the SUS [33]. The usability study had an overall sample size of 45, with 15 participants in each group.

2) User experience questionnaire (UEQ)

The UEQ is often used as part of a classical usability test to collect quantitative data about the participants' experience in using the system. This too is a 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 are 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 conventional training experience.
6. **Stimulation:** Describes the user's interest and excitement about the system and their interest to continuously use it.

The scale's efficiency, dependability, and perspicuity describe the pragmatic qualities (purpose-oriented) of the system, whereas the scale's novelty and stimulation relate to its hedonic qualities (non-purpose oriented).

E. 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 λ2 was calculated to measure the reliability of the UEQ questionnaire.

V. Results

The pilot usability study was conducted between January 2020 – August 2020 at the PMR Department at CMC Vellore. Fifteen patients, fifteen caregivers, and fifteen clinicians participated in the study. The patient group consists of 6 persons with stroke, 2 persons with traumatic brain injury, 1 person with Guillain-Barre syndrome, 3 incomplete spinal cord injury persons with lesion at the C8 neurological level, 2 persons with cerebral palsy, and 1 person with Parkinson's disease; the caregivers of these patients were recruited for the study. Among the 15 clinicians recruited for the study, 6 were occupational therapists, 5 were physical therapists, and 4 were physiatrists.

A. System Usability Scale (SUS)

The average score on the SUS for the clinicians, caregivers, and patients was 70.5 ± 12.5, 75.1 ± 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 > 72). 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. 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. All other questions had a neutral evaluation. The question "slow/fast" was the only question that was rated negatively with a mean score of -0.4 among patients. 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. 3); 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 the 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 λ2) was 0.64 and 0.69 among patients and clinicians, respectively.

VI. Discussion

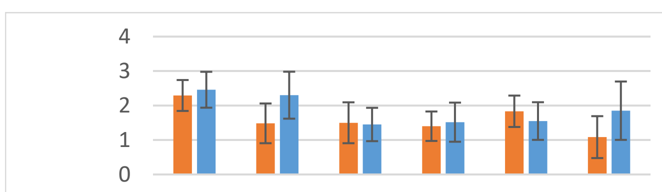
This paper described the design and preliminary evaluation of PLUTO, a modular, single DOF robot that can individually train four different hand functions through gamified therapy. This work demonstrates the potential of a single actuator system for addressing the need for training various wrist, forearm,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

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

These useful features are attained at the expense of the robot's ability to train multiple DOFs simultaneously. Therapeutically there is currently little evidence to support multi-DOF training's superiority over single DOF training [21]. Further, the patients requiring robot-assisted therapy are likely to be in the severe-to-moderate end of the impairment spectrum, and 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.

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 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; the method currently 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



	Attractiveness	Perspicuity	Efficiency	Dependability	Stimulation	Novelty
Clinicians	2.292	1.483	1.500	1.400	1.833	1.083
Patients	2.458	2.3	1.45	1.517	1.55	1.85

Fig. 3. User experience questionnaire sub-scale scores. All subscales had a positive score with no difference between the groups.

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 [34]. The viscous damping of PLUTO's 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 between 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. The universal hub used for plugging mechanisms to the robot must be replaced by a more straightforward approach, like a quick-release lock used in prosthetics devices. This would make attaching/detaching mechanisms easier and faster; it would be ideal if a patient can change mechanisms by him/herself with their less affected upper limb.
2. The current prototype has passive mechanisms to only train four essential wrist/hand functions. It is, however, possible to train various other functions (e.g., different types of grasps, finger/thumb training, etc.) through the design of appropriate additional mechanisms.
3. 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.
4. The current work has not explored the assessment of wrist and hand function with the robot, which would be essential to make maximum use of 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, which is 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 both 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 acceptable short-term usability, and it also helped identify features that need to be improved. 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 also patients' homes for delivering minimally supervised hand therapy.

VIII. Acknowledgment

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IX. Declaration of Interests

The authors declare that they have no competing interests.

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Figures

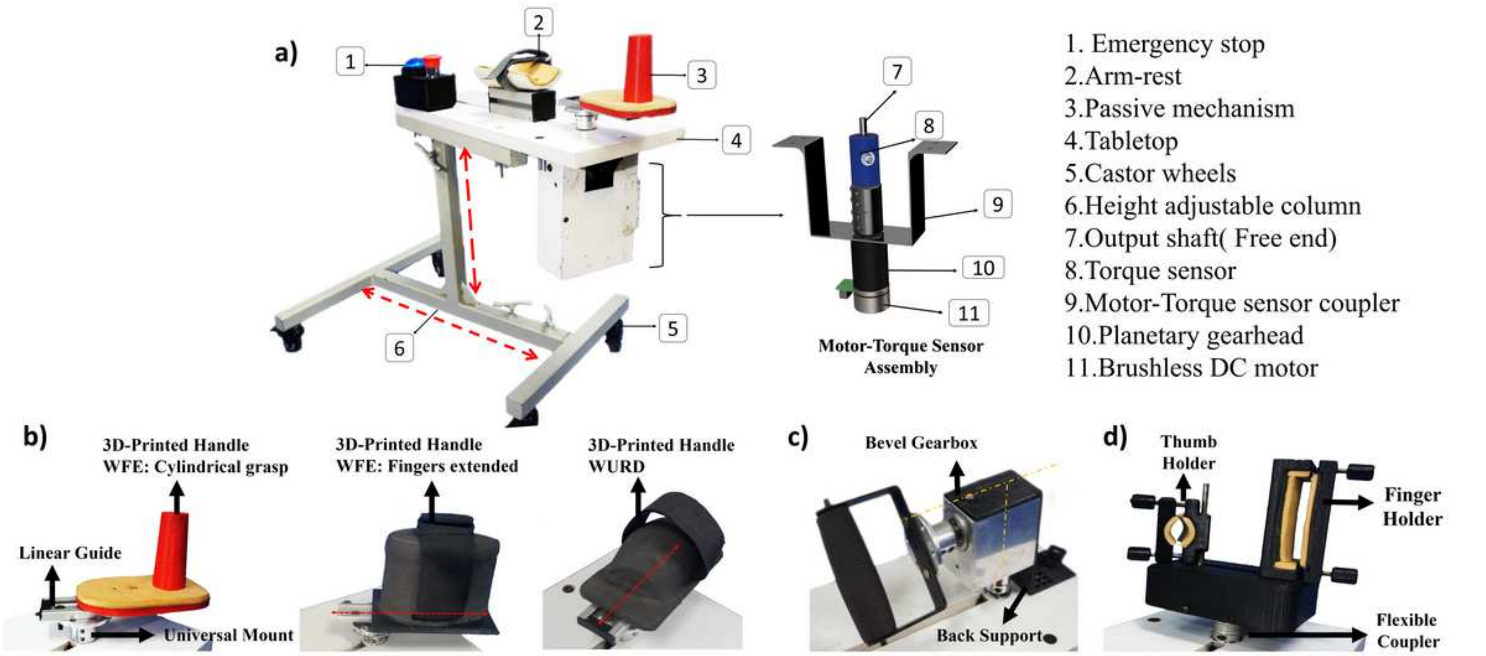

Figure 1

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

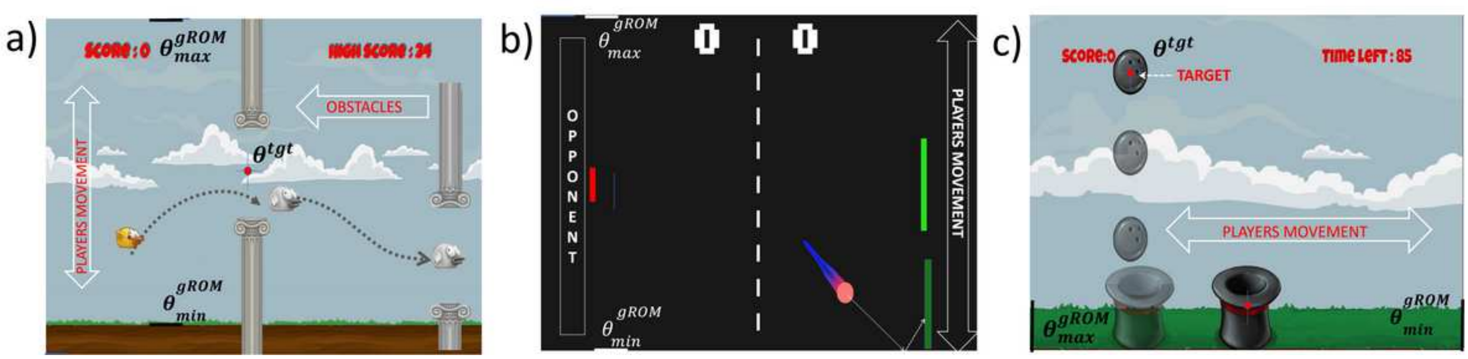

Figure 2

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.

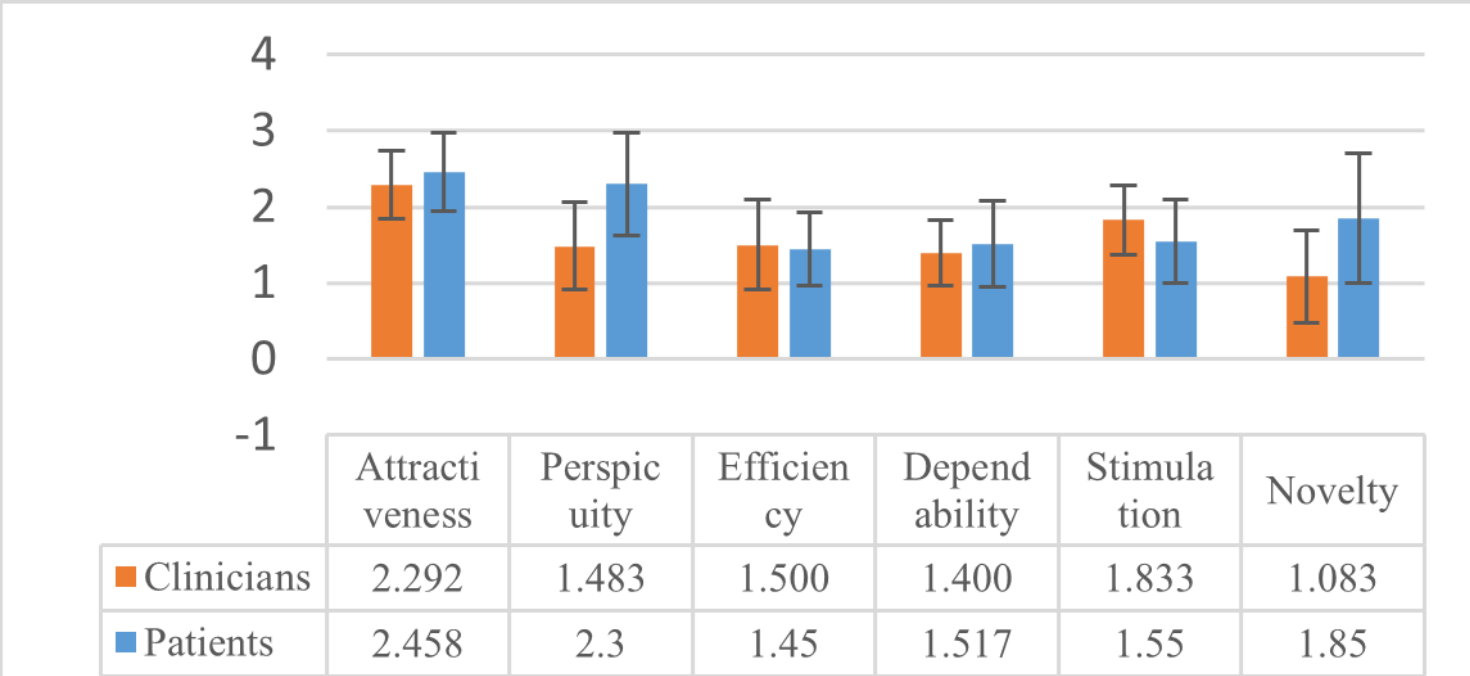

Figure 3

User experience questionnaire sub-scale scores. All subscales had a positive score with no difference between the groups.

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