Development of a Cable-Driven Robot with a Compensation Measurement System for Bimanual and Cognitive Rehabilitation of Stroke

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Abstract. *Stroke remains the leading cause of disability, causing significant motor and cognitive deficits such as function and memory loss. Recovery is based on neuroplasticity; wherein undamaged brain areas assume the functions of damaged regions. Bimanual robotic devices stimulate hemispheric activation and enhances neuroplasticity and recovery. This thesis introduced a cable-driven robot and serious games for bimanual and cognitive rehabilitation. A system was developed to measure compensation and distinguish motor recovery from postural adjustments. Two stroke groups underwent bimanual or cognitive exercises with serious games, leading to significant improvements ($p < 0.05$) in several parameters and clinical scales (Fugl-Meyer and Motor Activity Log).*
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Keywords: stroke rehabilitation; cable-driven; bimanual robot; serious games; cognitive; compensation.

1. Introduction

Stroke affects over 100 million people globally [WSO 2023]. Despite contemporary rehabilitation strategies, it remains a leading cause of disability, leaving many individuals with motor and cognitive deficits such as functional loss, limited mobility, spasticity and memory impairment, thereby significantly reducing their quality of life. Rehabilitation goal is to enhance function and foster independence in the Activities of Daily Living (ADLs) [Neil 2023], which are predominantly bilateral tasks.

In recent years, many robotic systems have emerged for rehabilitation purposes. Cable-driven robots stand out for their advantages: lightweight structure with small moving parts, large workspace, and inherent safety due to cable flexibility, allowing safe interaction with patients. Additionally, they are cost-effective and require minimal maintenance. Clinically, using cables instead of rigid links enhances user acceptance by reducing the sense of restriction for patients. These attributes make these robots highly suitable for rehabilitation applications [Alves et al. 2022].

1.1. Neuroplasticity in the Stroke Rehabilitation

Functional recovery following stroke is based on neuroplasticity mechanisms, wherein the brain can form new pathways and connections through increased exposure, allowing undamaged areas to assume the functions of damaged regions [Pila et al 2023]. Motor deficits improvements can be achieved by increasing cortical excitability in the affected hemisphere or by reducing the (hyper)excitability of the unaffected hemisphere [Alia et al. 2017]. In this way, it is critical to suppress negative plasticity (maladaptive), related

to hemiparetic patients adopting behavioral changes such as compensatory mechanisms that favor the unaffected limb use (learned nonuse) [Rocha et al. 2021].

Bilateral priming is an emerging strategy. It involves symmetric bimanual movements to catalyze motor relearning in the Upper Limb (UL) and aid neurological rehabilitation for patients with chronic and subacute stroke. Bimanual movements can be assisted by a robotic device, increasing the affected UL use, and reducing compensatory movements. High-intensity bilateral training using bimanual devices yielded to superior outcomes in Fugl-Meyer (FM) assessment and Stroke Impact Scale when compared to conventional/unilateral stroke rehabilitation [Hsieh et al. 2017; Chen et al 2022]. Additionally, using bimanual robots with the paretic arm increases hemisphere activation in both ipsilesional and contralesional areas during movement [Luft et al. 2004].

1.2. Cognitive Rehabilitation of Stroke

Early and intensive therapy is crucial for effective stroke rehabilitation, but conventional methods is often monotonous and repetitive. The use of serious games designed for rehabilitation have emerged as a promising alternative [Proença et al. 2018]. These games immerse patients in engaging experiences that make training exercises more enjoyable and less strenuous [Bonnechère 2018]. Moreover, studies integrating robotic devices with serious games [Pila et al. 2023] indicate similar or superior arm function improvements.

Force feedback encourages symmetrical force application in the paretic arm, counteracting overuse of unaffected limb, thereby preventing learned nonuse [Van Delden et al. 2012]. Score and variables such as force and time, correlate patient progress with clinical scales and allow auto-calibration of game attributes such as difficulty and assistance level to optimize the therapy for each patient [Aguilar-Lazcano et al. 2019].

Stroke constitutes a risk factor for memory impairment, a significant health issue among the elderly population. Logic/puzzle games can contribute to the evolution of the brain region involved in memory [Kühn et al. 2011], and cognitive training with attention and memory tasks effectively enhances these skills in stroke patients regardless of age, allowing the transference of this learning to ADLs [Gamito et al. 2017].

Adding robotic bilateral priming and non-invasive brain stimulation (e.g., serious games) into traditional therapy combats learned non-use and interhemispheric inhibition. This approach promotes cortical excitability rebalancing and fosters a neuroplastic environment conducive to motor and cognitive recovery [Abdullahi et al 2023].

1.3. Measurement of Compensation in the Upper Limb

Accurate and objective evaluation of UL movement quality is essential to comprehend motor deficits and intervention effectiveness [Schwarz et al. 2020]. Compensation is commonly employed during stroke rehabilitation and, while it may provide immediate benefits, it hinders long-term recovery and can cause orthopedic issues. It is defined as incorporating additional degrees of freedom (DOF) in other joints or body segments to adapt to the motor function loss [Cai et al. 2019]. Typical UL compensatory patterns include excessive forward trunk lean, trunk rotation, and shoulder elevation, Figure 1.

To effectively mitigate compensation, an automated detection system and suitable intervention are necessary. Current commercial assessment systems are costly and limited. Inertial sensors offer a cost-effective solution to accurately detect movement

across multiple body parts without external references. These sensors are increasingly used in sports tracking and healthcare application [Schwarz et al. 2020; Saes et al. 2022].

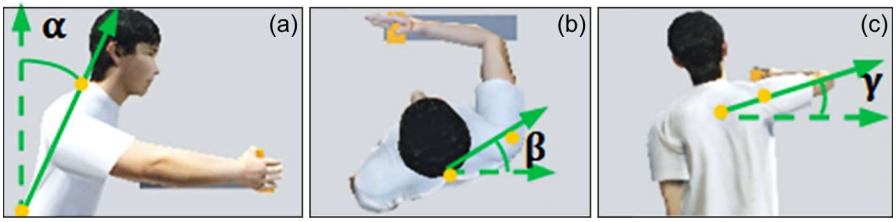


Figure 1. Representation of compensation patterns: (a) forward trunk lean (α), (b) trunk rotation (β), and (c) shoulder elevation (γ). Adapted from Cai et al. [2019].

2. Design of a Novel Bimanual Cable-Actuated Robot System

This thesis presents a low-cost, cable-driven robot for bimanual rehabilitation, designed to encourage even use of both arms. Costing under $1,000, it offers an affordable solution for increasing robotic presence in rehabilitation clinics.

2.1 Design procedure and characteristics for BiCAR

The Bimanual Cable-Actuated Robot (BiCAR) is a 2 DOF cable-driven robotic structure featuring an aluminum frame and a handlebar end-effector (Fig. 2). It includes two modules, each consisting of a DC motor, pulley, load cell, and rotary encoder, enabling, in this configuration, rotation over z-axis and translation over y-axis, Fig. 2a.

The motors, powered by 24 V DC, provide up to 48 N.m peak torque and 46 W power, with speeds up to 45 RPM. Position proportional control is managed by an Arduino Mega with Matlab and a VNH2SP30 motor driver (2 actuators up to 30 A), adjusting motor speed via PWM to achieve the desired position based on the current difference. A monitor on the T-frame improves posture (Fig. 2b-yellow). For safety, the control unit is enclosed (Fig. 2b-red) and a button cuts power and stops motors in emergencies (Fig. 2b-green). A button allows quick start/stop of actions or games (Fig. 2b-blue). Tests showed satisfactory accuracy in reproducing predefined trajectories with average errors of 0.35 ± 0.27 cm (2.33 ± 1.83%) [Alves et al. 2019].

2.2 Kinematic model of BiCAR

The BiCAR allows planar trajectories with two actuated cables; dynamics and inertial effects can be neglected due to low mass and speed. The device is under-constrained in the +z direction, requiring an external force to fully determine the mobile platform's posture [Blanding 1992]. The user, aided by an additional weight, imposes a force on the platform to maintain cable tension and downward movement. Rotational movements require adjusting cable lengths: decreasing the left and increasing the right rotates clockwise (CW), and vice versa for counterclockwise (CCW). Equal length changes move the bar up or down.

Figure 2c depicts variables for modeling: desired bar height and orientation (h/θ), W_b (distance between modules) which is centrally aligned with O_{XYZ} reference and W_g (handlebar), and cable lengths L_1 and L_2; θ is given as a function of cable lengths, Eq. (1):

$$\theta = \frac{\cos^{-1}\left(\frac{-4L_1^2 + W_b^2 + 2W_g^2 + 4h^2}{4W_g\sqrt{\frac{W_b^2}{4} + h^2}}\right)}{2} - \frac{\cos^{-1}\left(\frac{-4L_2^2 + W_b^2 + 2W_g^2 + 4h^2}{4W_g\sqrt{\frac{W_b^2}{4} + h^2}}\right)}{2} \quad (1)$$

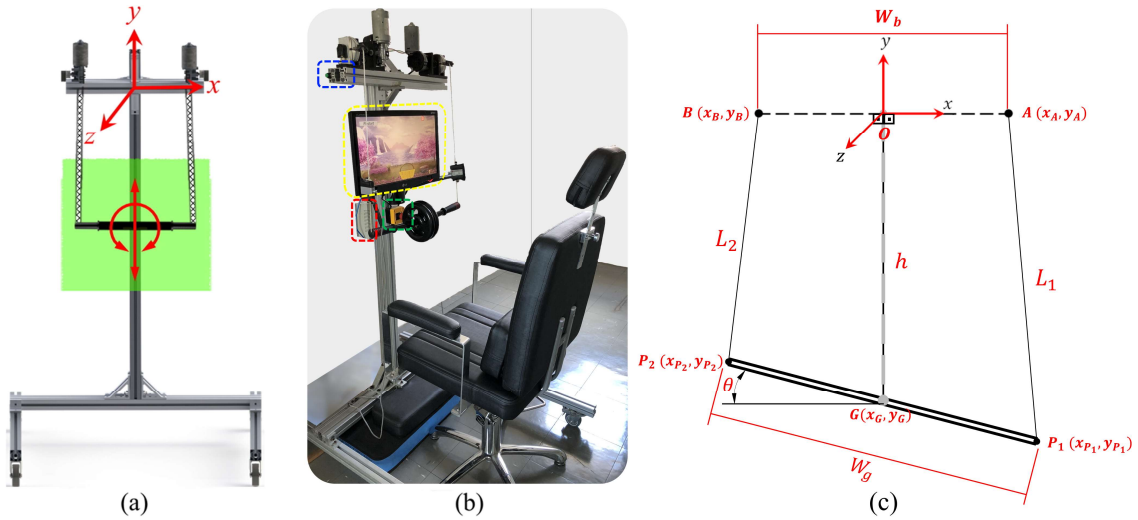


Figure 2. Bimanual robot: (a) DOF, (b) components highlight and (c) schematic.

2.3 Serious Games Developed for Bimanual and Cognitive Rehabilitation

The MineCart game, Fig. 3a, was designed in Unity and Matlab [2023] for rehabilitation training with the proposed bimanual cable-driven robot. In this game a wagon moves to pick up crystals that fall from the ceiling, using as input the rotation movements of the bimanual robot (CW/CCW). To rotate the handlebar, the user indicates the intent by applying a force difference ΔF between the sides. A greater force on the right side rotates clockwise; otherwise, it rotates counterclockwise. The game requires patients to use both limbs, including the affect one, to rotate de handlebar, preventing reliance on the non-paretic side (learned non-use). The score is proportional to the number of crystals caught, with a hidden score (losses) determining the level of assistance. Assistance initially facilitates and eventually auto performs the movement. Additionally, movements in the wrong direction are more difficult to perform.

Stroke can affect a person's ability to perform precise and coordinated movements, including the ability to fit objects. In this context, therapy pegboard has been used as an accessible and effective tool to recover fine motor coordination. The pegboard aids to develop the ability to manipulate objects with precision, allowing patients improve performance in ADLs, such as dressing or feeding. Furthermore, they improve attention, concentration, and the visual spatial cognition of patients [Chien et al. 2023]. Thus, in this thesis, a memory game combining reach and pegboard fit was developed for training cognitive and fine motor function: the Color4Memory game (Fig. 3b).

In this game, patients observe and memorize 4 geometric shapes/colors with a 10-second timer, then reproduce the sequence on a pegboard with the real pieces. Level progress sequentially based on patient performance, with challenges and variations tailored to each session, ensuring memory reinforcement. Auditory feedback is given at each new level and when time expires. Additionally, the pegboard is positioned based on the patient's maximum reach capacity, promoting an increase in the range of motion and improving the Reach and Grasp activity. Thus, this activity has a broad spectrum of benefits in rehabilitation, enhancing range of motion and fine motor skills while boosting cognitive functions like attention, reaction time, and memory.

Figure 3. Main screen of the serious games: (a) MineCart and (b) Color4Memory.

3. CADS: Compensation Assessment and Detection System

The Compensation Assessment and Detection System (CADS) was created to correlate movements and joint kinesiology, allowing biomechanical analysis to distinguish actual recovery from postural adjustments. CADS, consists of six three-dimensional wearable sensors (peripheral), Figure 4, designed to complement the proposed serious games.

3.1. Design Requirements for the CADS

Key requirements for CADS development included: low weight and wireless to maintain patients' natural movement; low energy consumption for wireless operation without large batteries attached; no need for external references or markers; non-invasive; low setup time and easy/quick calibration. Each peripheral device comprises an Arduino Nano microcontroller (ARM cortex M4 version) for processing/transmitting data, an IMU LSM9DS1 module, additional sensors (Sense 33), and Bluetooth Low Energy transmitter (nRF52840), totaling 5 grams. These components are powered by batteries. The central device is a PC/laptop with a Bluetooth LE receiver.

CADS power source is LR/PR41 button-type batteries. Each battery has an approximated voltage of 1.5 V and are widely used in medical devices like hearing aids, thermometers, among others. The microcontroller supports up to 21 V, allowing to safely stack 10 or more batteries in series to achieve the desired autonomy. These batteries reduces both weight and maximum current, making them safe for operation in rehabilitation environments. Furthermore, the low current/power is not an issue, as the other components in this project are classified as ultra-low consumption.

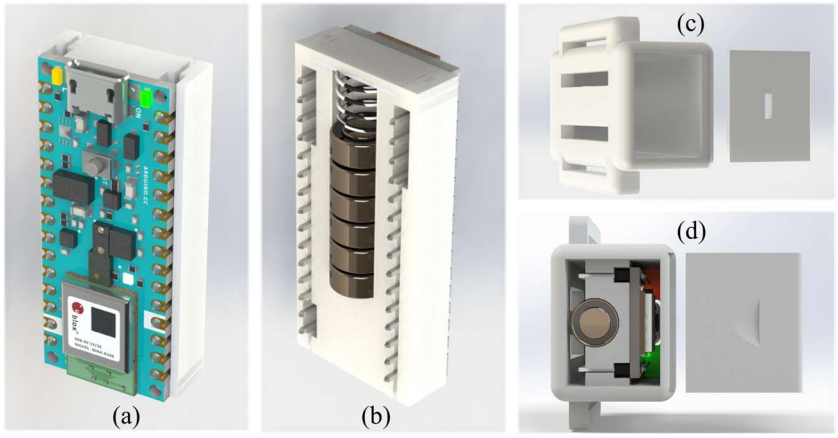


Figure 4. CADS design: (a) core, (b) batteries, (c) enclosure and (d) sliding cover.

3.2. Sensors Positioning of the CADS

The sensors positioning is shown in Figure 5: sensors S_1 and S_2 on the right and left shoulders, respectively; S_3 and S_4 on the arms; S_5 on the sternum; and S_6 on the lumbar region. This arrangement targets three main types of compensations: shoulder elevation (S_1/S_2) and forward tilt and trunk rotation (S_5/S_6). Sensors on arms measure range of motion and help analyze compensation values. Miotec straps, known for their progressive resistance, adjustability, and comfort, are used to attach sensors to the body.

Lumbar sensor serve as an initial reference. Since patients are immobilized at the waist, there is little to no movement in this area. Post-data collection, processing is carried out to express information in absolute global coordinates, $O_{x_0y_0z_0}$, aligned with body axes/planes, regardless of sensor; x_0 axis aligns with the transverse axis (e_t), y_0 coincides with antero-posterior (e_a), and z_0 aligns with longitudinal (e_l). Additionally, the x_0y_0 plane coincides with the transverse plane, x_0z_0 with the coronal (frontal), and y_0z_0 with the sagittal.

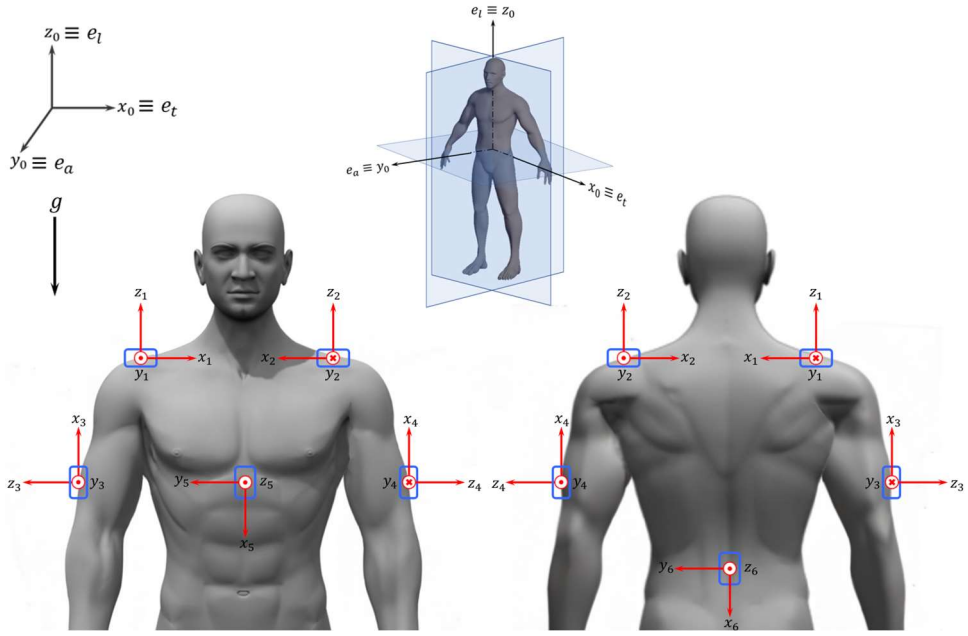


Figure 5. Diagram of the CADS sensor placement on participants.

3.3. Data Calibration and Processing

A considerable limitation associated with the use of inertial sensors is related to the accuracy of measurements, which relies on successful sensor calibration, appropriate filtering and fusion algorithms, alignment between sensors and body planes, and accurate estimation of movement amplitudes [Morrow et al. 2017; Schwarz et al. 2020].

Therefore, each sensor is pre-calibrated across all respective axes of accelerometer, gyroscope, and magnetometer before robotic therapy sessions. An additional calibration based on Schwarz et al. [2020] was performed using data obtained from standard movements of 10 subjects to establish a common global reference for all sensors aligned with body axes and planes.

During acquisition, raw accelerometer and gyroscope data are recorded at 200 Hz, magnetometer at 80 Hz. Data were synchronized with 5-millisecond precision and filtered

using a Butterworth low-pass filter. Velocity integration deviations are corrected using a Kalman filter, and gyroscope orientation variations are reduced through zero velocity updates. The Sensor Fusion and Tracking Toolbox™ is used to estimate orientation, position, and angular velocity. The ahrsfilter fusion filter is used to fuse IMU/MARG data, providing a smooth orientation estimate and robustness against environmental noise sources as this filter can also detect and reject magnetic interferences ensuring no alteration in orientation estimate [Roetenberg et al. 2005; Mathworks 2022; 2023].

After data fusion, phase unwrapping is performed to convert cyclic orientation data into a continuous format. This process detects and eliminates discrete jumps in measurements, caused by transitions between maximum and minimum angles. This ensures continuous and reliable data interpretation.

3.4. Validation of the CADS Prototype with an Industrial Robot

To ensure that operational requirements are met with the intended performance/accuracy, a validation was conducted using a CADS sensor mounted on an industrial robot's end-effector. Rotational movements around all robot axes were executed and compared with CADS measurements. Validation was performed at three distinct velocities (V_1, V_2 and V_3) configured in the industrial robot parameters (20, 200, and 1500 mm/s, respectively).

Results show that higher velocities increase orientation measurement errors: $1.55^{o}\pm0.77$ (0.44%) for V_1, $2.58^{o}\pm1.50$ (0.82%) for V_2, and $7.12^{o}\pm2.74$ (2.56%) for V_3. However, velocity V_2 best represents human movements in rehabilitation scenarios, where peak speeds typically do not exceed 150 mm/s [Rohrer, Fasoli and Krebs 2002; Bressi et al. 2023]. This aligns with the clinically accepted values by the American Medical Association (AMA) for reliable movement assessments ($<5^{o}$), making it valuable tool for tracking in stroke rehabilitation [Majumder et al. 2021].

4. Results and Clinical Tests

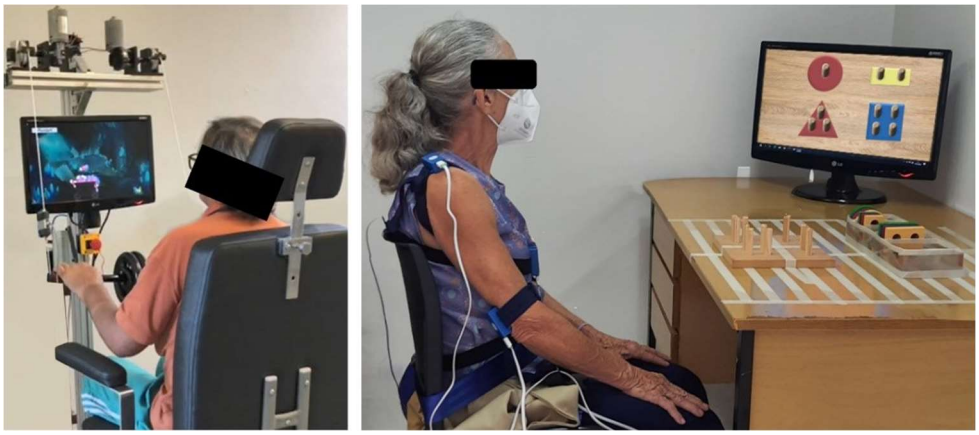
To conduct the tests, this project was submitted and approved by the Research Ethics Committee. The participants were divided into a group of 10 healthy subjects and two groups of patients with impaired joint movement and memory due to stroke. The results obtained with the healthy participants were used as baseline and an average goal for post-stroke patients.

4.1. Description of Clinical Tests

Post-stroke patients were divided into two protocols groups as detailed in Table 1. Second protocol sessions have 3 segments divided equally between: both UL, non-affected UL, and affected UL usage only. The setup of both protocols can be seen in Figure 6. Concomitantly, these patients underwent conventional rehabilitation therapy sessions three times a week, each lasting approximately 50 minutes.

Table 1. Summary of protocols for post-stroke patients.

	Participants	Months post stroke	Age (Years)	Duration	Sessions/ Week	Activity
First Protocol	10 stroke hemiparetic	6.0 ± 2.1	58.4 ± 9.7	5 weeks	2-3 (30 min)	Bimanual UL exercises using BiCAR with the MineCart game
Second Protocol	3 stroke hemiparetic	20.3 ± 15.3 (chronic)	70.3 ± 2.1	6 weeks	3 (30 min)	Reach training with UL using CADS and Color4Memory game



(a) (b)

Figure 6. Post stroke patients' setup for (a) first and (b) second protocols.

Clinical data, including time, force, and movement trajectory, were collected through sensors in the BiCAR and CADS. This data, along with other game-specific information, were used to evaluate patients' performance, compensation, and progress.

4.2. Bimanual Progress Evaluation with BiCAR and MineCart Game

The performance parameter evolution for the first protocol is summarized in Table 2. This table compares the first session (I_1) with the last session (I_2). Statistically significant differences (*) are indicated ($p < 0.05$). The t-test for mean differences was used.

The intervention significantly improved game scores and reduced losses for all patients. Movement completion time (T_m) decreased, while reaction time (T_r) increased, being the sole parameter to worsen, though this change was not significant. Mean/peak angular velocity (ω_m /ω_p) significantly increased, and movement smoothness parameters (number of peaks N_p/normalized jerk J_n) decreased, indicating smoother and continuous movements. Force exerted increased on both sides, but force symmetry (δF) improved, indicating even use of both arms. Torque (τ_{tot}) shows a non-significant increase. Significant improvements (*) were observed in ω_m, ω_p, $F_{p_{dir}}$, $F_{p_{esq}}$, δF, score, and losses.

Table 2. Evolution of performance parameters (1st protocol).

	Score (*)	Loss (*)	T_r (ms)/ T_m (s)	ω_m/ω_p (rad/s)*	N_p/ J_n (s^{-2})	$F_{p_{dir}}/F_{p_{esq}}$ (kgf)*	δF (kgf)*	τ_{tot} (kgf.cm)
I_1	155 ± 65	40 ± 12	1029 ± 569/ 4.6 ± 1.1	0.25 ± 0.07/ 0.49 ± 0.13	4.1 ± 1.1/ 1.82 ± 1.00	2.82 ± 1.14/ 2.73 ± 1.06	0.94 ± 0.63	1.65 ± 9.64
I_2	199 ± 88	17 ± 15	1247 ± 574/ 4.1 ± 0.9	0.32 ± 0.05/ 0.62 ± 0.12	3.7 ± 0.4/ 1.63 ± 0.30	3.74 ± 0.59/ 3.48 ± 0.69	0.70 ± 0.63	5.58 ± 6.93

4.3. Compensation and Performance Evaluation with CADS

The Reach and Grasp test, a common tool in rehabilitation programs to enhance arm and hand function, was applied to investigate limb synergies tied to post-stroke motor impairments. This test was associated with Color4Memory game and pegboard to analyze compensatory movements. Initially, the test was performed with both ULs (T_{G_1}), and then with the non-affected and the affected ULs (T_{G_2} and T_{G_3} respectively).

The protocol's effect was evaluated through CADS extracting descriptor angles and compensatory movements. The results are summarized in Table 3, comparing healthy

participants (H_0) with post-stroke patients from the second protocol, and contrasting the admission week (I_1) with discharge (I_2).

Significant improvements ($p<0.05$) in the shoulder (β_L) and arm descriptors (β_t and β_a) were observed during the use of the affected UL (T_{G_3}) for all patients, indicating a shift in movement preference towards the affected side. Trunk inclination (α_5) varied, either increasing (T_{G_2}) or decreasing (T_{G_3}), but both to moderate values, which is expected as even healthy subjects exhibit adjustments with an average amplitude of around 25º to aid movement [Schwarz et al. 2020]. Minimal amplitudes might suggest limited movement, potentially due to spinal mobility restriction or muscle weakness, while larger values indicate excessive compensation, which leads to stability issues and injury risks.

Shoulder compensation combines the displacement involving shoulder elevation and forward inclination and varies per individual and deficiency but is generally small (2 to 4 cm). This compensation is not healthy or functional, but an attempt to bypass body limitations or deficiencies. Combined shoulder compensation (γ_c) and trunk displacement (ε_5) amplitudes decreased only when using exclusively the affected limb (T_{G_3}). During non-affected UL exclusive segment (T_{G_2}), no changes were observed (except for trunk inclination), which is consistent, as amplitude improvements on the unaffected side are not expected. Due to lumbar immobilization, no amplitudes were observed on this sensor (S_6). As no T_{G_1} parameters significantly changed, they were not represented in this set.

Table 3. Evolution of CADS descriptor angles/displacements (2nd protocol).

	Shoulder $\beta_L(T_{G_3})$*	**Arm** $\beta_t(T_{G_3})$*	**Arm** $\beta_a(T_{G_3})$*	**Trunk** $\alpha_5(T_{G_2})$	**Trunk** $\alpha_5(T_{G_3})$	**Shoulder** $\gamma_c(T_{G_3})$	**Trunk** $\varepsilon_5(T_{G_3})$
H_0	20.6±5.1º	52.5±7.9º	37.9±3.4º	28.4±13.0º	26.8±16.4º	1.0±0.2 cm	1.5±0.2 cm
Week 1 (I_1)	12.5±1.5º	16.5±6.2º	20.3±7.4º	22.6±8.1º	33.5±13.2º	3.4±1.0 cm	2.6±0.6 cm
Week 6 (I_2)	20.2±1.1º	31.7±7.4º	27.2±6.7º	25.4±11.7º	25.7±5.0º	2.3±0.5 cm	2.1±0.1 cm

4.4. Reach and Cognitive Evaluation with Color4Memory Game

Reach and cognitive evolution ($I_1 \rightarrow I_2$) of post-stroke patients with Color4Memory game are summarized in Table 4, comparatively with healthy participants (H_0).

Firstly, the maximum distance reached was measured by the Modified Functional Reach Test [Marchesi et al. 2021]. After six weeks of therapy training, the reach distance for patients increased by an average of 10% (30.0 to 33.3 cm). In comparison, healthy participants had a reach distance ranging between 35 to 60 cm (45.5 cm). The average time required to complete each memory level decreased remarkably for the patients (91.73 to 39.98 s), approximating from the H_0 group results (35.74 s). Additionally, a greater reduction occurred when patients used the affected UL. The H_0 participants completed all the 16 game levels with each side and correctly matched the order/color at an average of 15 levels (94%), while patients showed a significant improvement, increasing from 6.3 to 12.9 levels and improving their match rate from 59.0 to 84.4%.

Finally, the weighted score significantly improved from 76 to 354 ($p < 0.02$). This parameter represents improvements in both cognitive (attention, reaction time, and memory) and motor function, as faster progression leads to increasingly challenging memorization levels. H_0 group's results ranged from 740 to 1000 (max), averaging 930.

Table 4. Evolution of cognitive parameters (2nd protocol).

	Max. Distance Reached	Average Time	Number of Matches	Levels Completed	Matches (%)	Weighted Score
H_0	45.5 ± 7.6 cm	35.74 ± 4.03 s	15.0 ± 1.0	16 (All)	94.2 ± 7.1	930 ± 88
Week 1 (I_1)	30.0 ± 8.7 cm	91.73 ± 68.80 s	3.8 ± 0.8	6.3 ± 3.2	59.0 ± 11.2	76 ± 53
Week 6 (I_2)	33.3 ± 5.8 cm	38.98 ± 8.64 s	9.6 ± 3.3	12.9 ± 6.1	84.4 ± 6.3	354 ± 140

4.5. Evaluation of Post-Stroke Patients by Clinical Scales: FM and MAL

Patients were clinically assessed at the beginning/end of the protocol (I_1/I_2) using the motor function domain of the Fugl-Meyer [1975] assessment and the Motor Activity Log (MAL) [Pereira 2012].

Fugl-Meyer Scale

In the initial patient's assessment, FM score was 51.7 ± 11.4, indicating marked functional impairment. Upon reassessment, patients showed a significant increase achieving a score of 63.0 (mild functional impairment). The effect size, assessed using Cohen's D, was large (1.0). Additionally, the Minimum Clinically Important Difference (MCID) for stroke rehabilitation therapies reported by the Shirley Ryan database [2023] indicates a 10-point increase for the Fugl-Meyer scale for upper limbs based on post-stroke patients averaging 70 years old, thus this protocol difference (11.3 points) is clinically significant. Moreover, this value exceeds the MCID for chronic stroke patients related to gripping ability (4.25), releasing ability (5.25), arm movement ability (7.25), activities of daily living (4.25), and overall UL function (5.25).

Motor Activity Log – MAL

According to the analysis of responses, there was a 62% improvement in quantitative numerical data in the final MAL compared to the MAL 1. The effect size determined by Cohen's D was large (2.0). In the qualitative scale, there was a significant increase in the quality of use of the affected upper limb by 66% when comparing the final MAL with the first MAL (paired t-test, $p < 0.05$); the effect size determined by Cohen's D was large (4.7). The MCID for MAL in post-stroke rehabilitation is an increase of 1.0-1.1 points; thus, the difference found in this protocol is clinically significant for both the quantitative and qualitative scales of MAL [Shirley Ryan 2023].

5. Conclusions

This thesis explores the development of a bimanual cable-actuated robot and a compensation measurement system for stroke rehabilitation, highlighting its benefits in motor-functional recovery and hemispheric brain activation. It also outlines the role of many serious games developed for bimanual and cognitive rehabilitation of stroke, MineCart and Color4Memory, respectively. Validation results confirmed the developed devices and sensors achieve satisfactory accuracy for application in stroke rehabilitation.

Two protocols involving bimanual robotic therapy with MineCart game and cognitive therapy with Color4Memory game were administered to post-stroke patients. Patients' performance and progress were evaluate based on measurable parameters such as time, speed, movement smoothness, force, reach distance, range of motion, compensation, and scores. The first protocol demonstrated significant improvement in 7

parameters ($\omega_m, \omega_p, F_{p_{dir}}, F_{p_{esq}}$, δF, score, and losses) ($p < 0.05$), highlighting the progress in bimanual tasks performance for post-stroke patients through a serious game.

Second protocol investigated improvements in cognitive and compensation evaluation to assess whether the therapy outcomes were due to motor recovery or patient postural adjustments/compensations. Significant improvements in the shoulder (β_L) and arm descriptors (β_t e β_a) were observed for the affected upper limb, indicating an increased use of the paretic arm during training. Trunk inclination (α_5) showed a general trend towards moderate amplitude values, and some patients showed reduced values of shoulder (γ_c) and trunk compensation (ε_5). The Color4Memory game parameters showed an increase in average reach distance and a decrease in time to complete each memory level. Additionally, all score-related parameters improved significantly.

These improvements enable patients to perform the ADLs more efficiently, leading to increased independence and quality of life, as confirmed by clinical improvements in the FM and MAL scales. Future work involves interpreting brain activities during rehabilitation, adding multiplayer elements to serious games, and using Artificial Intelligence to automatically analyze motion data and identify compensation patterns.

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