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Design and Evaluation of 4-DoF Machine for Improving Muscle Control and Upper Extremity Rehabilitation

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Poor upper limb movement control and coordination are major problems in patients with stroke. A novel combination of muscle and multi-joint movement increases mobility, allows for the degree of freedom in shoulder and elbow joint, and facilitate patients to learn and control their movement. The assisted movement with a symmetrical counterweight balance system and real-time feedback is proposed to enhance and facilitate the movement of paresis muscles. The power assist uses purely mechanical and assisted movement from the non-paretic arm. The feedback system receives data from a three-axis load cell sensor on both sides of the handlebar during movement and feedback force from both sides in real time. The display of real-time feedback is provided and enables subjects to adjust and correct their movement. Two combined movements were performed in five healthy subjects for testing the device system and correlation of force from the load cell and muscle activity from surface electromyography (sEMG). The results showed that the new upper limb rehabilitation machine with feedback and a symmetrical counterweight balance system can achieve mass balance in all positions. The device is robust, safe, and easy for the subject to move a combined movement of the shoulder joint and elbow joint. The force from the load cell sensor occurs simultaneously with muscle activation during movement. This system helps the patient to learn and control their force from the paretic limb. The high repetitions from practice with an accuracy of muscle force and movement control will enhance motor learning and facilitate motor recovery during the rehabilitation period.

Keywords: bilateral arm movement, counterweight balance, feedback, rehabilitation, upper limb training

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INTRODUCTION

Stroke is one of the main diseases that cause disability and death. The number of stroke patients is rapidly increasing (Sarikaya *et al.* 2015) and causes almost one-third of disease-related deaths worldwide (Feigin *et al.* 2015). Upper limb deficits persist in as many as 60–70% of stroke survivors (Rabadi 2011). Most upper limb deficits involve muscle control, strength, coordination, perception, and dexterity of movements. These problems affect activities of daily living (Langhorne *et al.* 2009). Up to 77% of stroke survivors (Parker *et al.* 2020) are unable to use their hands and arms in activities of daily living. The commonly used in upper limb rehabilitation are repetitive task training, task-specific exercise, or goal-oriented training. The objective of the rehabilitation program is to stimulate brain learning and induce neuroplasticity in the damaged part of the brain (Langhorne *et al.* 1996; Teasell *et al.* 2003). Nowadays, new technologies and devices are implemented and commonly used in rehabilitation programs. Robots and assistive devices have been developed to promote motor recovery and facilitate upper limb movements. They were designed to achieve accuracy of movements with high repetitive training for promoting motor learning and motor control. The information during movement will enhance and improve neuronal plasticity in the brain. Moreover, these also help to reduce the workload of physical and occupational therapists and increase the patient's motivation to train (Tomić *et al.* 2017).

Upper limb rehabilitation devices can be divided into unilateral and bilateral training machines. The unilateral or single limb movement machine is used to enhance movement in the paretic limb; for example, Armeo spring, Armeo power, SaeboMAS, and ArmAssist (AA). The motor is used to generate force and assist patients in moving their paretic limb. It has an adjusted mode that can be adapted to the patient’s abilities. However, several studies have recommended that bilateral training has better clinical efficacy even with limited upper extremity functionality (van Delden *et al.* 2012), and especially when used for coordination training (Whitall *et al.* 2011). Bilateral training facilitates the movement of the flaccid arm and has synchronization coordination in bimanual performance (Stoykov and Stinear 2010). The bilateral rehabilitation devices consist of BATRAC (Tailwind), Reha-Slide, APBT (the Rocker), and Able-X, *etc.* The robotic parts have EXO-UL7, Bimanual Handlebar, and Bi-Manu-Track, among others (Summers *et al.* 2007). Patients with mild stroke have been found to improve significantly with bilateral training compared with unilateral training (Whitall *et al.* 2011). Interest in bilateral training is increasing because most daily activities require both arms.

Bilateral training is a movement in which two arms are connected. This movement affects the motor system through the coupling effect of the same muscles on both sides, thereby stimulating the functional recovery of the paretic side. The movement consists of symmetrical movements and asymmetric modes (Kelso *et al.* 1983). Bilateral symmetrical training stimulates the pathological hemispheres to be more active and improves the control of movement. It also affects the brain’s ability to change or form new neurons (neuroplasticity). The bilateral movement training improves many brain circuits; the supplementary motor area, primary motor cortex, and other regions of the brain that control movement (Donchin *et al.* 1998, 2001; Stoykov and Corcos 2009). In addition, improvement in trunk stability was noted (Donchin *et al.* 2002; Stoykov *et al.* 2009). During bilateral training, core stabilization muscles were more active than during unilateral training (McCombe Waller and Whitall 2008). A stronger body core affects the ability to control proximal limb movement (Donchin *et al.* 2002).

However, the device has some limitations: it can only move certain planes; does not cover normal movement; has no system to assist paretic side movement, force sensor to detect force, or support arm system; costs very high compared with the functionality gain, and is often limited to large centers or hospitals with specialized medical personnel. The solution to these limitations may involve designing the device to encompass movement and incorporating an assistance system for motion. For instance, utilizing a motorized system for power assistance can help augment the mobility of the patient's weakened arm and support the arm's weight during training. Furthermore, the arm support system may incorporate elements like springs for assisting movement. To address the limitation regarding the lack of an arm support system, it can be corrected by implementing a gravity balancing mechanism. This can be used in the development of an arm support system and a novel pure mechanism for rehabilitation devices.

Currently, gravity balancing mechanisms are commonly used in industrial, service, and medical robots, as well as in construction. Gravity-balancing mechanisms are currently being used in medical devices for support and fatigue relief. One example is the development of a tool-holding arm machine that can change its angle and position. In addition, there are also medical devices on the operating side with a balancing adjustment according to the change in weight (Tarnanen *et al.* 2008).

However, there are no upper limb rehabilitation devices that take advantage of the gravity balancing system in conjunction with a counterweight balance. The objective of this study is to develop a novel bilateral symmetrical upper limb with feedback and a counterweight balance system device for stroke patients that focuses on overcoming various limitations. The focal points consist of covering movements and getting real-time feedback. The device assists movement by force from the non-paretic arm and the mechanism of linkages and a counterweight balance system.

MATERIALS AND METHODS

The design and development of the device aimed to emphasize the creation of training devices under the condition that must be movable in all directions, affordable, and designed with a mechanical system without using motors. Additionally, it should incorporate sensors to create a detection system for exertion force and a feedback display. Furthermore, it should be capable of storing and analyzing data. After development, there was sensor processing testing for implementation and providing feedback to users, along with a pilot study conducted on healthy subjects.

An end-effector device for bilateral training was designed and developed. It was a bilateral device that helped to stimulate both limbs and trunk muscles, resulting in better control of the arm. It had an active assist system for the non-paretic arm to assist the paretic arm and uses a sensor to provide real-time feedback during training. The device was able to be moved in different postures with weight compensation. The advantage of a counterweight balance system is that the patient can move more easily and feel weightless. This makes it easier for patients to train and move more frequently. The device had a sensor that detects and displays forces on both arms to provide feedback and promote more effective training. The display screens were divided into two parts: the physiotherapist's part for control and analysis data and the patient's part to stimulate the movement and give feedback on the effort during targeted training. The result was displayed in real-time using a recording system for later analysis.

Overall Design of Bilateral Upper Limb Rehabilitation Device with a Symmetrical Mechanism

The device consisted of two main components – namely, the machine component structure and feedback. The design of the device started with determining the range of motion for different gestures to create a range of motion. This range was based on values obtained from body measurements (anthropometry) and then used the values obtained to calculate the distance of the two arm movements. A range of motion was used from the workspace of movement or specifying the achievable configurations of the end-effector with SolidWorks simulation software to know the total distance of arm motion caused by the movement of the device. By using the distance data of both arm movements to create a three-dimensional image with a computer program, it was possible to analyze the working distance of the machine. The motion module connected the base module to the component. The mechanism eight-linkage stalk was an essential point of the mechanism. The overall mechanism is illustrated by the diagram in Figure 1a. The calculations to determine the linkage length must be proportionate to the mass weighting to obtain a system of counterweight balance mechanisms. The linkage provided a range of motion in the direction of the arm up and down. The other end of the rod was attached to the slide rail. The slide frame moved on the slide rail. There were belts on the slide rails for symmetrical linkage movement or force transmission for left and right movement. The designed device was able to cover a normal range of motion.

Design Mechanism of the Device

The design mechanism consisted of two main parts: the motion of the device and the weight compensation. After the design of the mechanism, the safety factor was calculated to test the structure and safety of the device.

Design of the Movement of the Device (Range of Motion)

Due to the user's arm mobility, which allows freedom of movement around the body, it was necessary to use the forward kinematics equation. This is a method for determining the position of the end-effector (x, y, z), whereby the angles of movement were specified. This information will indicate whether the mechanism adequately accommodates the user's body movement based on the position of the moving end-effector. The study was based on mean body composition lengths associated with upper extremity movement dimensions of a six-foot tall male body with the following values: height of 188 cm, arm length of 78.2 cm on each side, and a body width of 40 cm (Nakamura 1996). The mean value was taken as the basis for determining the design values along with the normal human range of motion of the upper limbs with the following values: shoulder flexion 180°, shoulder extenson 60°, shoulder horizontal abduction 120°, shoulder horizontal abduction 30°, elbow flexion 60°, and elbow extension 60°. With this designed device, the user's range of motion will occur covering the normal range of human motion. Calculating the range of motion of the device began by determining the length of links.

To calculate the range of motion of the end-effector of the device, the forward kinematic equation was applied by calculating the angle change of Link 1, Link 2, and slide axis. The origin point was set at X_0, Y_0, Z_0. The

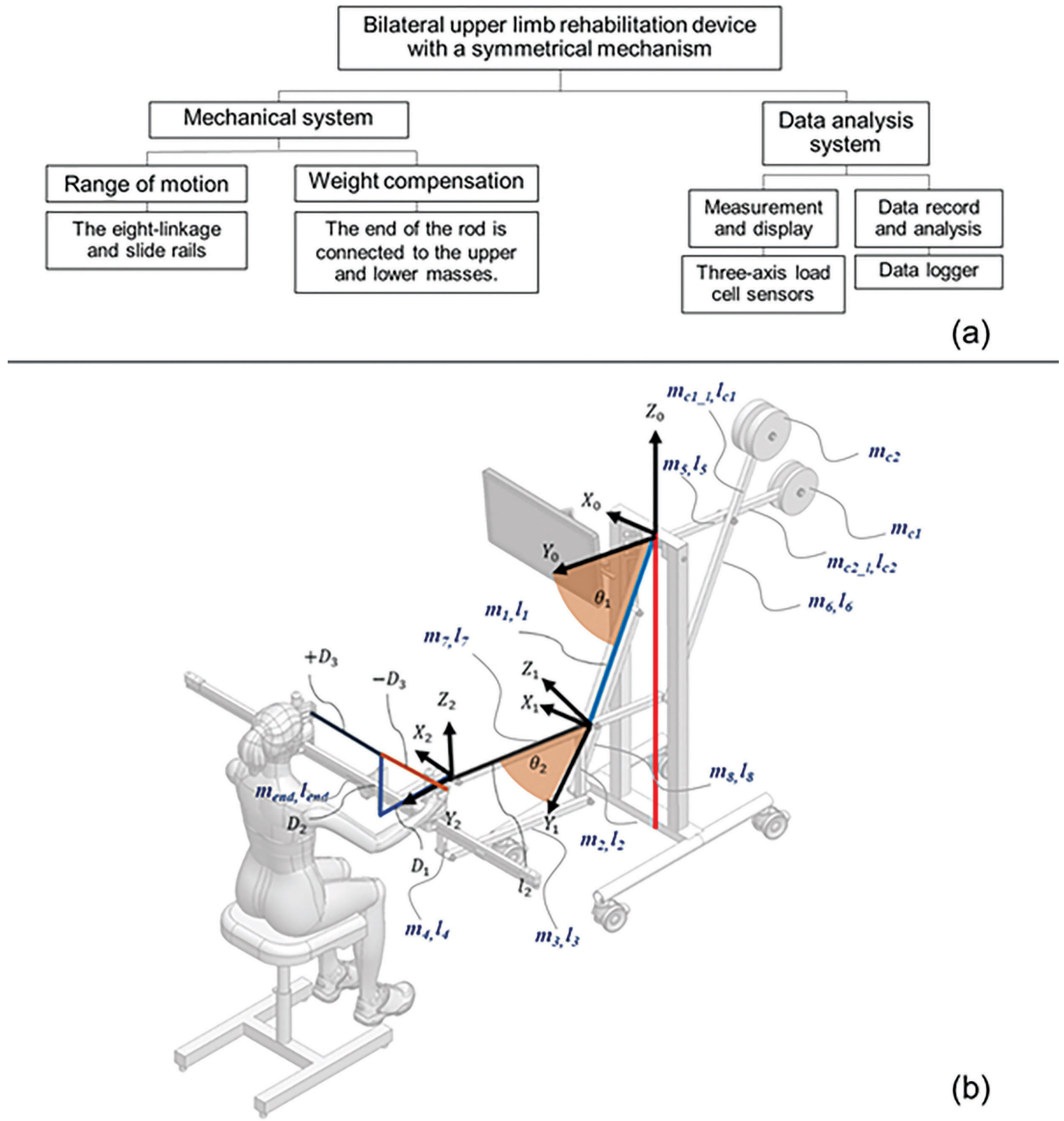

Figure 1. The overall mechanism and the calculation points of the range of motion and the components of the device. [a] The diagram provides a visual representation of the overall mechanism. [b] The points and lengths of the links are used to calculate the workspace or range of motion of the device.

relationship of the equation is illustrated below (Ben-ari and Mondada 2018).

This is the forward kinematic equation:

$$Y = (l1cos\ (\theta 1) + l3cos\ (\theta 1 + \theta 2) + d1) \tag{1}$$

$$Z = (l1sin\ (\theta 1) + l2sin\ (\theta 1 + \theta 2) + d2) \tag{2}$$

$$X = (\pm d3) \tag{3}$$

which gave θ_1 as a change in angle of l_1, whose initial angle distance was θ_1 min = 10°, θ_1 max = 82°. θ_2 is considered a change in angle of l_3, whose initial angle distance is θ_2 min = 28°, θ_2 max = 150°. The ±d3 is the sliding distance l_{end}, which will move on the slide rail. The values θ_1, θ_2,

l_1, l_3, and d3 were taken and substituted in Equations 1, 2, and 3, as shown in Figure 1b.

The limit of the angle refers to the angle that Link 1 of the devices can move up to the maximum is 760 mm. The value was substituted from the reference value of anthropometry or an average value of human segment lengths expressed as a percentage of the body into the equation to find the lengths of the links that form the eight links connected, as shown in Figure 1b.

After calculating the link lengths of the devices, they were then used to calculate the workspace or range of motion of the device. Figure 2 shows that the origin point (0,0) was set at the top of the pole frame, and the seated person was approximately 75 cm from the position (0,0) to the toe while sitting. Blue represents the movement of Link 1 (Stoykov and Stinear 2010) from Figure 2 on the origin point, which was connected to Link 2, represented by green when Link 1 and Link 2 were moved at different degrees of movement. The distance of Links 1 and 2 resulted in the movement of the end-effector. It was found that the position of the end-effector covers the normal human range of motion.

The workspace of the two upper limbs was based on a subject 188 cm tall under the bilateral upper limb rehabilitation device with counterweight balance through a symmetrical mechanism configuration. The workspace was analyzed based on the handle in combination with the movement of the hands, as shown in Figure 2.

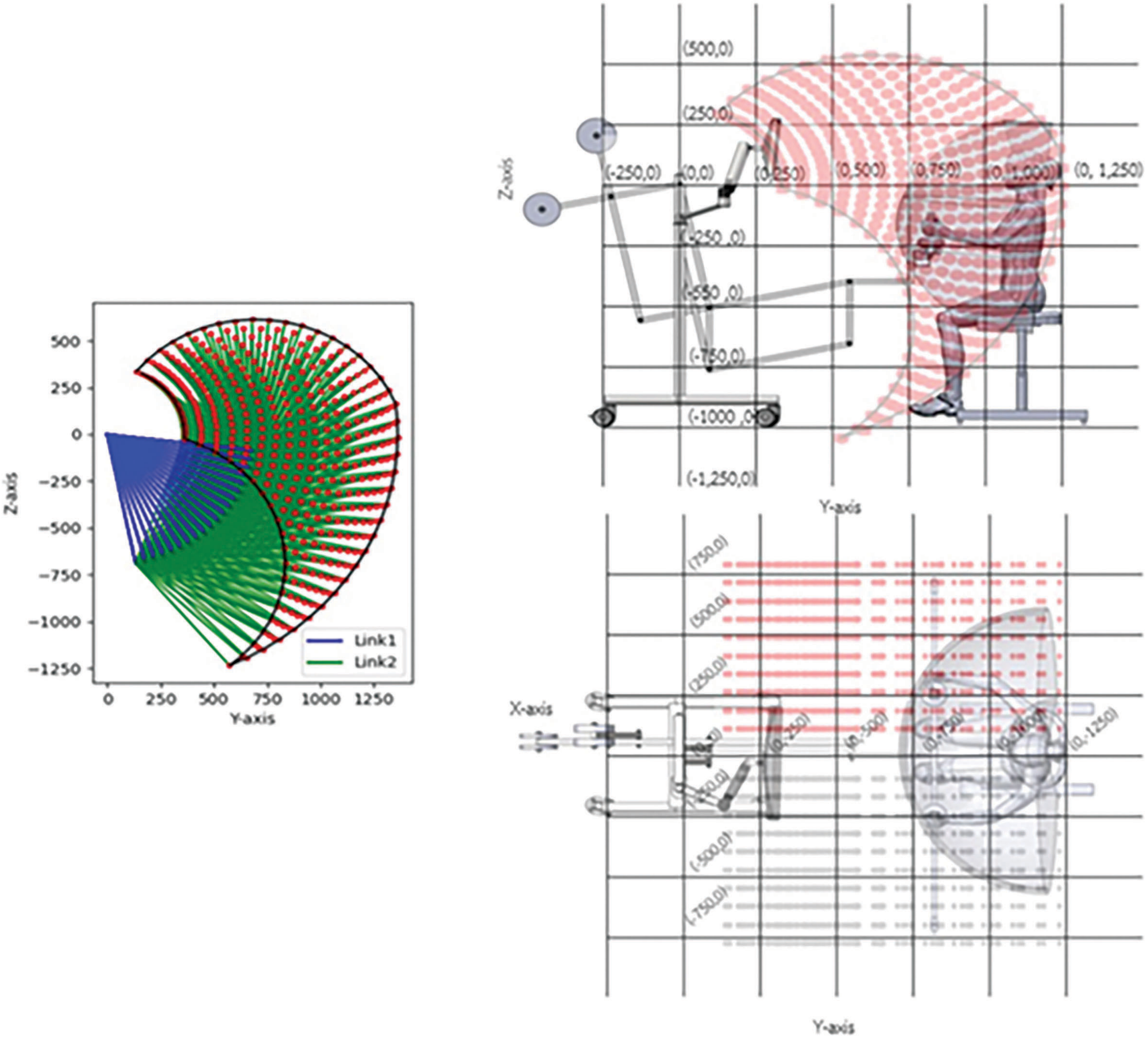

Figure 2. The distance of movement. The distance of movement of a person using the device in millimeter units.

The 3D graph showed the workspace of each arm, with the red dot indicating the right arm displacement workspace and the gray dot indicating the left arm displacement. The movement in the x-axis direction of each arm was 750 mm, the distance of travel in the y-axis direction of each arm was 1,250 mm, and the z-axis was 750 mm. The shaded area represents the normal range of motion of the human upper limb.

Design of Weight Compensation of the Device

The base module component structure consisted of two main poles that hold the articulated mechanism's eight-linkage stalks to create a range of motion up and down in the direction of the arm. In addition, the other end of the rod was attached to the slide rail. The slide frame moved on the slide rail. There were belts on the slide rails for symmetrical linkage or force transmission of left and right movements. In this case, the end of the rod was connected to the upper and lower mass to lower the weight at the handlebar position. The difference point of the mass gravity model in this study was based on the principle of counterweight balance. The principle implies that a gravity load plays a significant role in terms of energy efficiency. Balancing mechanisms increase the efficiency of the active device by helping to reduce the driving torque. In addition, the user can use the device without feeling the force of gravity as in a passive device. Currently, this mechanism is widely used in construction, industrial, and service applications, as well as in medical robots (Singh *et al.* 2016). Gravity compensation has been used in various applications. There are two approaches for designing a gravity balancing mechanism – namely, a counterweight or a counter spring. Gravity compensation with a counterweight is a method of balancing a mechanism by placing weights on the opposite side of the center of rotation. In the method with a spring, the mechanism is balanced by the restoring force of a spring instead of a counterweight.

Gravity compensation methods were used in various mechanism designs such as the design of a reactionless three degrees of freedom (3-DoF) planar parallel mechanism (Woo *et al.* 2019). A five-bar parallel mechanism using a counterweight was designed in (Fattah and Agrawal 2006). Moreover, a novel multi-DoF gravity balancing service robot arm with counter springs at each joint was developed by Tahmasebi *et al.* (2005). A multi-DoF robot arm can be counterbalanced by using springs for double parallelograms. This design is practical and compact.

The new design of a bilateral upper limb rehabilitation device with counterweight balance proposed in this study used equations from the study of Woo *et al.* (2019) to calculate the mechanical system of the device. A counterweight mechanism was designed to reduce the exertion on the device during movement, make the device lightweight, and decrease the device's weight from the effects of gravity.

From the equation, the calculation of counterweight balance in this study used mass at m1 and m2 to compensate for M(end). The length of each link was used to calculate the mass of the system. Once the length and weight of each link have been determined, the values in the equation were substituted: mass of Counterweight 1 as M_{C1} = 11.26 kg and mass of Counterweight 2 as M_{C2} = 8.46 kg. When substituting the equations, the equation were substituted: mass of Counterweight 1 as M_{C1} = 11.26 kg and M_{C2} = 8.46 kg.

Safety Factor of the Engineering Design of the Device Structure

The assumption of the simulation is the failure of the parts. In the case where the user exerts more pressure than normal on the device, this is a value obtained from calculating the factor of safety (FOS), which means that if the force exceeds the FOS considered normal, this sudden pressure will necessarily cause static load and equipment damage. A simulation modeling by SolidWorks simulation software for the case when the largest force was applied to the device, *i.e.* when the user applies a maximum pressure of 120 N, which in this case also causes the largest bending moment to the device. While the device was mass mounted behind M1 with 110.42 N and M2 with 82.38 N, the total force was 192.8 N. Calculation by the finite element method engineering program had a minimum FOS ratio of at least 3.

The FOS was used to show that the design considered that the workpiece could support more force than specified. From the simulation results, the most damaged area had a safety factor of 3, and this value was within the threshold. The general criterion is 2.5 or at least 2, which means that the device can withstand loads that are not less than three times the maximum force that the user can apply. In addition, the device was not deformed during use (yield stress) and the rocking frame contributes to safety and creates confidence among users. In addition, the device was manufactured according to the design and calculation process. Actual load tests were conducted, and it was found that the device withstands the force well and does not deform, so it is ready for use and safe.

From the stress calculation, when comparing the von Mises stress (or the stress applied to an object at a level von Mises stress of $8.169\ 7 \times 10^7$ MPa and the yield strength of 3.5×10^8 MPa), it was found that this value does not exceed the yield strength, indicating that the device and the material used can withstand the force.

Feedback (Three Axis Load Cell Sensor Processing System)

The structural design of the mechanical system was obtained by eight-linkage. This may cause the device to move in two planes (up-down, left-right), whereas the front and back direction was developed from the part of the slide rail mounted on the slide frame (horizontal movement mechanism). The pulley frame was connected with the handlebars on both sides, which transmit the force symmetrically for the left and right.

These allow the non-paretic arm to help the paretic arm move in the desired direction. The feedback system was another important point developed to cover the limitation of unknown information about changes during training or progression of the rehabilitation program. A three-axis load cell sensor (X, Y, Z) on both sides of the handlebars was used to receive exertion forces in three planes of motion. The signal was transmitted to the data logger and presented symmetrical or asymmetrical force exertion through the display.

Verification of the Processing of the Three-axis Load Cell Sensor

To verify the consistency of muscle activity obtained from the sEMG measurements of the upper extremity muscles and force from the three-axis load cell sensor during movement, five healthy subjects aged 18–40 yr old in good physical health and capable of understanding and following instructions were included. The subjects who had problems in the musculoskeletal system and a history of surgery affecting the range of motion of the upper limbs and hands were excluded. The test procedure of data processing was testing movement simultaneously with the measurement of muscle function with surface electromyography (Noraxon model Ultium sEMG).

The methods for these tests were as follows: the electrodes were placed on three muscles – namely, the biceps brachii, brachioradialis, and anterior deltoid. After that, the subjects performed two movements: [1] shoulder flexion and [2] elbow flexion with two conditions – namely, force exertion on both sides or force exertion on the dominant side only (right side). Three cycles of movement were performed during each movement. The data were obtained from the load cell by recording the load simultaneously with the sEMG signal. The values of the sEMG signal were processed in terms of root mean square. The values obtained from the three load cell cycles were made up of 100 datasets by calculating the average of all data. The data from sEMG and load cells were compared to determine the relative of muscle activity and force exertion.

The study was approved by the Human Research Ethics Committee of Thammasat University (Science: HREC-TUSc; COA No. 082/2564), and informed consent was obtained from all participants.

RESULTS

Development Results

The bilateral upper limb rehabilitation device is shown in Figure 3. The functions of the device functions, which are considered the strengths and differences from the existing equipment are explained as follows:

The concept of movement is a mechanical system without a motor that uses a non-paretic limb, real-time feedback, and active participation. It produces symmetrical

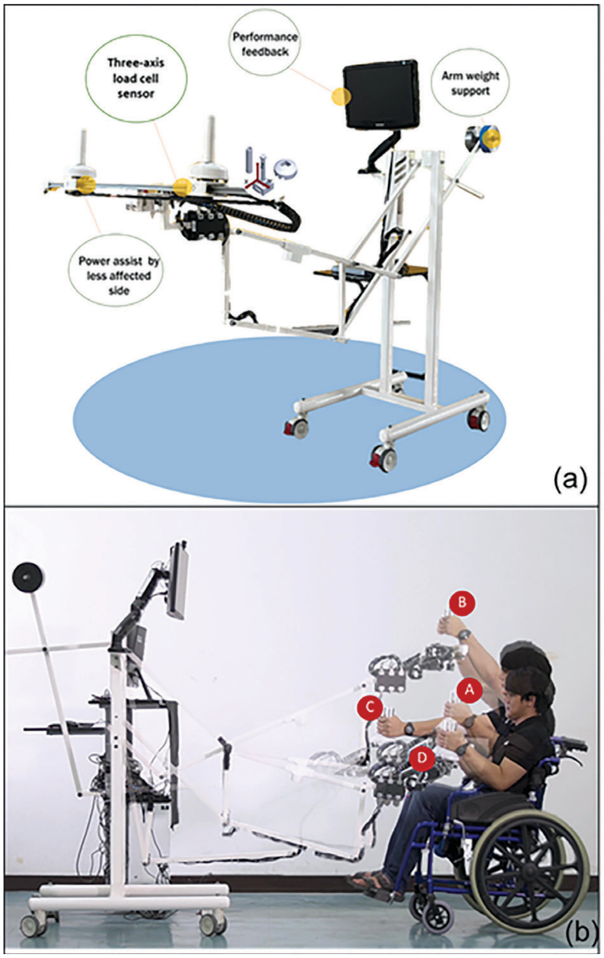

Figure 3. The final version of the device. [a] The key features of the new bilateral upper limb rehabilitation device involve counterweight balance through a symmetrical mechanism and feedback. [b] The relationship between arm movement and counterbalance.

movements of both arms. The device stimulates the non-paretic limb to move and promotes the work of the proximal limb and trunk muscles (McCombe Waller and Whitall 2008). It also includes the coordination of the use of both arms, which is the highlight and the difference from the training of the unilateral side.

The device provided a combination of movement of the upper extremity. It is composed of a 3-DoF shoulder joint (flexion/extension, horizontal abduction/adduction, internal rotation/external rotation) and a 1-DoF (one degree of freedom) elbow joint (flexion/extension). The device was able to move in a variety of movements. For example, shoulder flexion at 90° combined with elbow flexion/extension plus shoulder flexion and abduction with elbow flexion/extension or circumduction of the shoulder joint with elbow flexion/extension. The supporting of arm movement used eight-linkage and weight compensation with a counterweight balance system. The support of the paretic arm assists patients to move more easily and encourages them to actively participate in the training. Regarding the relationship between arm movement and counterbalance, the relationship can be shown in Figure 3b, where A represents the counterweight position based on the movement position from the counterweight point. There can be different weights of the mechanisms that act as follows: B represents the force pulling from the mechanical system downward, which is approximately 30 N when lifted from the counterweight position. C represents the outward force exerted by the mechanical system, which is approximately 37 N when pushed from the counterweight position. D represents the force pulling from the mechanical system upward, which is approximately 35 N when pressed down from the counterweight position. The design aimed to incorporate a slight increase in load, in addition to accounting for the weight of the user's arm.

The real-time feedback occurred when load cell sensors on both handles received force, transmitted signal through the data logger, and displayed the data as a percentage of force exertion on the screen. The four levels of percentage (25, 50, 75, 100) indicated symmetrical/asymmetrical exertion between both limbs. Twenty-five percent (25%) indicated force exertion from the paretic limb (0–25%) compared to the non-paretic limb. The asymmetrical force from both arms presented as 25–75%, whereas 100% indicated symmetrical force. Patients need to adjust and collect their force until they reach 100%. In this way, the patient can experience feedback about their exertion in real time. This is an important point that differs from the available, conventional devices. For this reason, this device is one that truly encourages the patient to train their weaknesses.

Experimental Results

Five healthy subjects (three males and two females) were recruited in this study. The average age was 26.2 ± 1.64 yr (minimum of 25 yr; maximum of 29 yr), and the average height was 166.6 ± 6.11 cm (minimum of 159 cm; maximum of 172 cm); they were right-handed. Each subject was tested by first attaching EMG electrodes to different locations of the main muscles. Then, the subjects were asked to perform flexion of the elbow or flexion of the shoulder. For each movement, the subjects performed the movement under the following conditions: exertion of force on both arms and on one arm (dominant side), as well as grasping of the other arm without force; three times were performed in each condition. The level point of the starting point was controlled. According to the results of the study, presented on the processing verification of a three-axis load cell sensor, it was compared to the EMG in performing movements under certain conditions. According to the principle of receiving the force, forces are applied in three directions or in the three-axis directions, so the resulting force is the sum of the resulting forces. However, each movement has one main force axis, which represents the movement in that axis.

Figure 4 (middle) shows the exertion of the movement in elbow flexion (y-axis), in which the exertions of both arms were equal. From the graph, all five subjects had similar force exertion on both sides, which is consistent with the specified conditions. Comparing the three-axis load cell sensor data to the force exertion and the muscle activity from the sEMG showed similar activity in the same direction (Figure 4; bottom). The biceps brachii and brachioradialis muscles were active throughout the total force generated in the load cell.

Figure 5 (middle) shows the exertion of the movement during shoulder flexion (z-axis), where the exertion occurred only on the right side. The graph shows similar trends of the load cell and sEMG result (Figure 5; bottom).

DISCUSSION

The bilateral symmetrical upper limb rehabilitation with feedback and counterweight balance system device in this study was designed to overcome the existing limitations of the previous device. The design of a pure mechanism with eight linkages together with slide rails allows movements in the x, y, and z axes. The patient's arm is supported with a counterweight balance system. A belt was attached to the slide rail to create a linked movement of the left and right arms (Figure 3a). The system is adjustable for different bilateral upper limb training (shoulder flexion-extension, shoulder horizontal abduction, elbow flexion-extension, and combined movements). The force from the non-

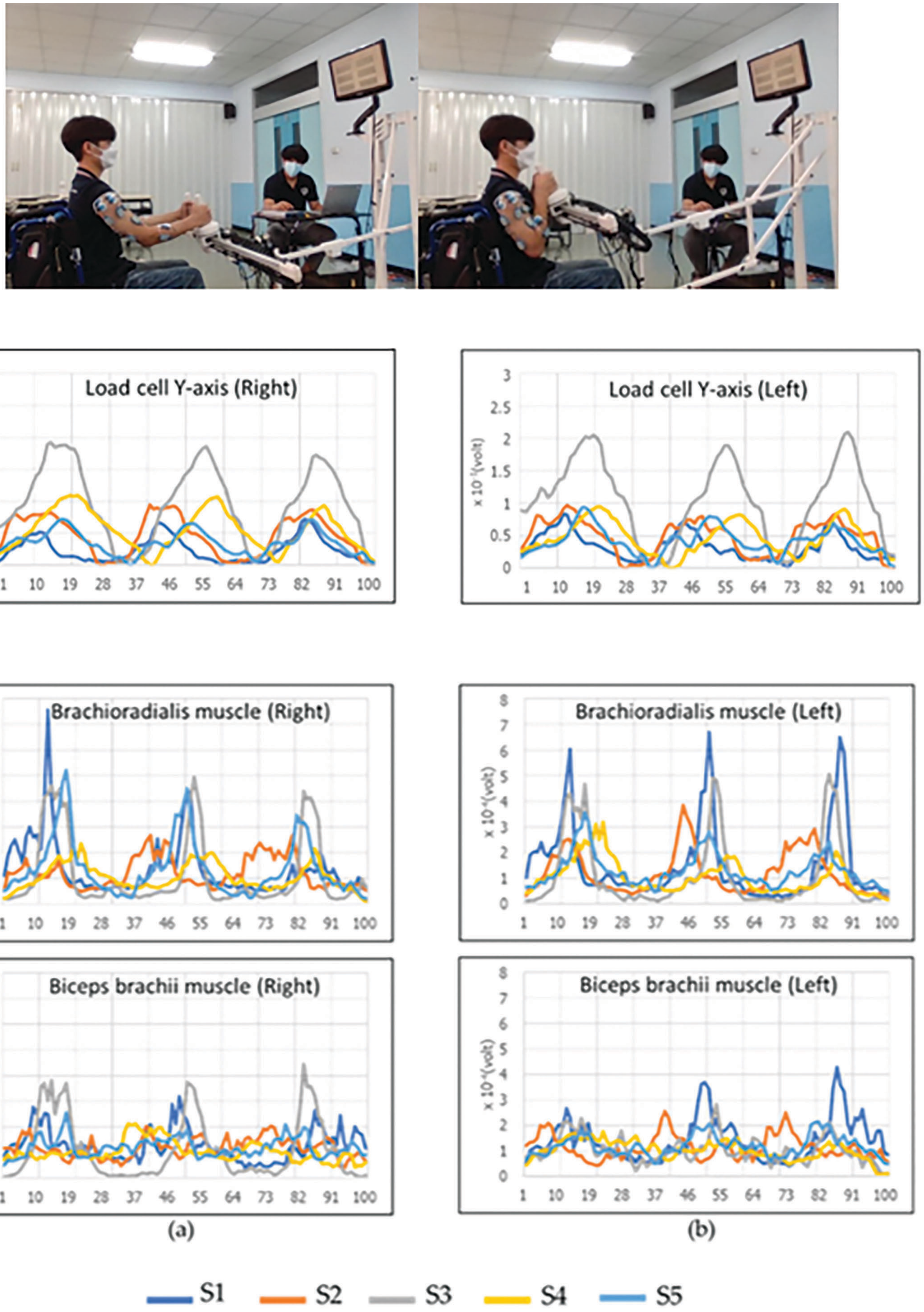

Figure 4. Position of the arm during elbow flexion movement.

Figure 5. Position of the arm during shoulder flexion movement.

paretic limb and a counterweight balance system assisted the patient's paretic limb in moving simultaneously. These helped the weaker muscles to function and allowed patients to complete tasks by themselves.

Moreover, the device was equipped with a three-axis load cell sensor and placed on both sides of the handle. The load cell sensor was easy and convenient to apply with the device. It provides guidance and real-time feedback during movement. Both sensors received force from all three directions that were sent to display on the screen. Real-time feedback challenges the patient, encouraging more active engagement and helping them to learn, correct, and optimize their force. The muscle force detected by the load cell sensor occurred at the same time as muscle activity detected from surface EMG (Figures 4 and 5). It represented the changes in muscle activity and control during complete tasks.

The bilateral symmetrical upper limb rehabilitation with feedback and a counterweight balance system device allows repetitive movements in the paretic limb. The improvement of motor learning and motor control was associated with neuroplasticity (Lee *et al.* 2022). The brain requires an accurate movement pattern, a variety of movements, an appropriate number of repetitions, and a balanced duration of training for effective recovery. Moreover, the movements during bilateral arm training resemble activities of daily living. It involves changes in bilateral descending motor pathways in the brain and influences the activation of postural control. This resulted in favorable changes in proximal upper limb movement control (Cirstea *et al.* 2006; Sethy *et al.* 2018).

The device with feedback and counterweight balance system enables shoulder and elbow of paretic limb move independently in varieties directions and had a combination movement more than previous devices (van Delden *et al.* 2012). For example, Reha-Slide is a device consisting of a board and two parallel slide rails (Buschfort *et al.* 2015). The device allows the shoulder, elbow, and wrist of the paretic limb to move independently and train the coordination of both arms, although the device in this study uses the bilateral arm training concept same as previous studies. Patients need to actively participate during the training and real-time feedback gives more information to the patients for adjusting force and control their paretic limb. The eight-linkages and counterweight balance system support the paretic limb and allows patients to move their limb more easily. Combined with non-paretic limb movement simultaneously allows the patient to learn appropriate movement and control their joint to move in a full range of motion in each direction. Real-time feedback helps the patient and therapist communicate with each other and show progress during the training period. In addition, the feedback provided information and made it easier for the patient to be active and aware of the changes in their movement.

The device is safe and effective in working for bilateral upper extremity rehabilitation. It is suitable for training combination movement in a variety of directions for stroke patients. However, this device still has some limitations. First, the size was too large and occupies more space that is not suitable for small areas. Second, there was little movement of the wrist and hand. The device does not aim to assist fine movement and is not suitable for patients who have severe spasticity or flaccidity in the upper extremity. Last, there is no movement of shoulder abduction/adduction and partial movement of internal rotation/ external rotation. Therefore, these movements should be added to the rehabilitation program.

Although the device has some limitations, it is probably useful for training. It meets the practical requirements and expectations of both the patient and the physiotherapist. The future is concerned, with the idea of increasing movement of the upper extremity in the direction of abduction/adduction and external rotation/internal rotation or diagonal movement-like activity in daily living. Preparing to develop games for enhancing the situation and motivation of training. In addition, clinical trials involving patients with stroke patients should be further studied to assess the safety, effectiveness, and usefulness of the devices.

CONCLUSION

The new bilateral upper limb rehabilitation device was developed to encourage patients to actively participate in the paretic limb. Eight-linkage and weight compensation with a counterweight balance system provided varieties of combination movement of shoulder and elbow joints. It supports the paretic limb, assists patients in moving their limbs, and encourages patients to do repetitive movements frequently. Moreover, real-time feedback gives information for patients to collect and adjust force more symmetrical to the non-paretic limb. The upper muscle control from symmetrical movement allows patients to do effective activity in daily living. Moreover, effective training comes from adequate repetitive movement and active participation from the device. This device may help stroke patients to improve their body in many ways by increasing the range of motion, muscle strength, motor control, and coordination of upper limb movement.

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