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The Technical Development of a Prototype Lower-Limb Therapy Device for Bed-Resting Users

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Abstract: It is generally recommended that bed-resting patients be mobilised early to promote recovery. The aim of this work was to develop and evaluate the usability of a prototype in-bed lower-limb therapy device that offers various training patterns for the feet and legs, featuring an intuitive user interface and interactive exergames. Based on clinical interviews, the user requirements for the device were determined. The therapy device consisted of two compact foot platforms with integrated electric motors and force sensors. Movement control strategies and a user interface with computer games were developed. Through a touch screen, the target force and position trajectories were defined. Using automatic position and force control algorithms, the device produced leg flexion/extension with synchronised ankle plantarflexion/dorsiflexion as well as leg pressing with adjustable resistive loading. An evaluation test on 12 able-bodied participants showed that the device produced passive (mean position control errors: 8.91 mm linearly and 1.62° in the ankle joints) and active leg training (force control error: 2.52 N). The computer games were proven to be interesting, engaging, and responsive to the training movement. It was demonstrated that the device was technically usable in terms of mechatronics, movement control, user interface, and computer games. The advancements in well-controlled movement, multi-modal training patterns, convenient operation, and intuitive feedback enable the compact therapy device to be a potential system for bed-resting users to improve physical activity and cognitive functionality.

Keywords: lower-limb training; in-bed therapy; force control; computer games; neuro-muscular rehabilitation

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1. Introduction

It is generally recommended that bed-resting patients be mobilised as early and frequently as possible [1]. Elderly individuals, patients with neurological disorders, or those in acute care often have to remain in bed for a prolonged period due to factors such as unstable physical status, impaired balance, or lower extremity muscle weakness [1,2]. It has been shown that muscle atrophy and decreased mobility are common challenges faced by patients after prolonged bed rest, particularly among the elderly and critically ill [2]. Early mobilisation is crucial for preventing these issues, as it helps maintain muscle mass, improve circulation, and accelerate recovery [3]. It has been shown not only to enhance physical outcomes but also to reduce the incidence of complications such as deep vein thrombosis and pressure ulcers [4]. Early mobilisation involves the physical activities of getting patients to move in bed, sit on the edge of the bed, stand up, and eventually walk [5]. However, in-bed mobilisation is often insufficiently implemented due to the demanding manual labor or insufficient staffing of the clinical team [6]. The gap between the urgent need for early mobilisation and the limited availability of training staff underscores the necessity for innovative solutions that provide effective in-bed exercise, engaging even the most vulnerable patients in essential physical training.

There are several products on the market to assist with training in bed, but the movement patterns need to be improved. Automatic assistance of the lower limbs is achieved by activation of the thigh or the foot. A representative example of the system for thigh activation is the robotic bed system ErigoPro [7]. The system consists of a tilt table with two actuated thigh cuffs and two spring-supported foot plates. It allows patients to practise hip and knee flexion with limb loading on the tilt table. Another robotic system, Vemotion [8], features a mechanism that allows for easy installation on individual beds, eliminating the need for patient transfer. It also allows hip and knee flexion in a lying position. A third approach to early rehabilitation is the use of in-bed cycling devices. The system bemo (THERA-TRAINER Medika Medizin Technik GmbH, Hochdorf, Germany) is a robotic-assisted over-bed cycling device for early mobilisation. It consists of a frame with a pair of cycling pedals. The height and the cadence of the pedals can be automatically adjusted. The rollers at the bottom make it easy to align the bemo for the individual patient, whether lying or sitting on the bed. The Motomed Letto (RECK-Technik GmbH, Betzenweiler, Germany) consists of a standing frame, a drive unit, and two pedals [9]. It produces a circular foot trajectory for patients lying on the bed. In-bed cycling devices allow patients to exercise without leaving their beds. They have been shown to be acceptable, safe, and feasible for early mobilisation [10]. However, no significant benefit has been found [11]. It has been suggested that the intensity of exercise should be tailored to the patient's physical condition [12].

Based on the devices already on the market, we wanted to develop a compact lower-limb therapy device for in-bed usage that produced adjustable leg movement with dynamic loading on the foot. The first functional model was developed to include two foot plates that were actuated by pneumatic cylinders [13]. The air flowed inside the two cylinders. When one foot plate was pressed by the user, the other foot plate retracted reciprocally. The resistance could be adjusted by valves. Such an unactuated leg press did not require electricity or air compressors. After assessment by physiotherapists, the lightweight in-bed leg press was considered to meet the functional requirements for early leg mobilisation. However, the system only reacts to patients' active pressing on the foot plate. For patients who are too weak to press voluntarily, the device cannot be used effectively.

In order to allow usage by a large population, a new in-bed lower-limb therapy device was developed. The first iteration of a User-Centred Design process for such a device [6] yielded the following user requirements:

(1) It should be lightweight and compact for transport and storage;
(2) It should be easy to use, not only for clinical staff but also for patients without specialist supervision;
(3) It should provide therapeutic passive and active leg exercises;
(4) It should provide ankle dorsiflexion/plantarflexion; and
(5) It should provide an intuitive user interface with interactive exergames.

The aim of this work was to develop and evaluate the usability of a prototype in-bed lower-limb therapy device that offers various training patterns for the feet and legs, featuring an intuitive user interface and interactive exergames. This work presents a preliminary assessment of usability in able-bodied participants. Follow-up clinical studies will be conducted on end-users (patients and therapists) to evaluate clinical feasibility and investigate the effectiveness of the developed system.

2. Materials and Methods

The mechanical structure of the lower-limb therapy device is first described, followed by the development of the control strategies, programme architecture, and computer games. Subsequently, the system evaluation test on 12 able-bodied participants is detailed.

2.1. Mechanical Development

The lower-limb therapy device was designed in NX (NX2312, Siemens Switzerland Ltd., Zurich, Switzerland) and embodied in a prototype (Figures 1 and 2). As shown in Figure 1, four motors (EC60, maxon motor, Sachseln, Switzerland) were used to generate linear movement of the foot platform and ankle joint rotation. The linear movement of each foot platform was achieved by using a motor with a screw drive. The rotation of each ankle joint was achieved by using a motor with a gearbox (ratio of 40). Two force sensors (one-dimensional pull/press sensor; resolution 0.12 N; range of −500 N to 500 N; Bengbu Sensor Company, Bengbu City, Anhei Province, China) were mounted under each foot plate (Figures 1 and 2b) to measure the active force from the user. The force sensor was calibrated. The placement of the force sensors affected measurement accuracy and stability. The force sensors were fixed directly below the foot plate, removing the influence from the mechanical components on force measurement.

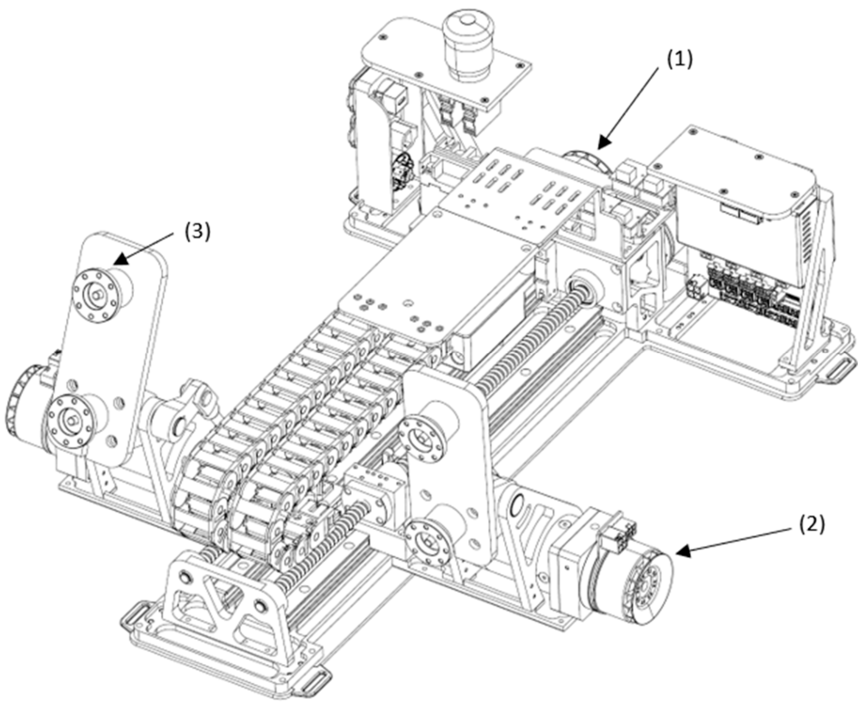
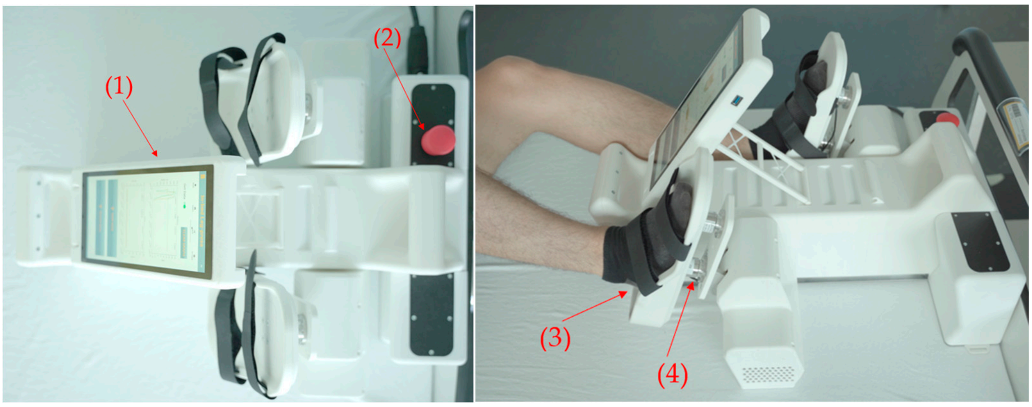


Figure 1. CAD of the lower-limb therapy device. The system housing, the foot plates, and the cases for the foot platforms were removed so as to show the drives and mechanical components. (1) Motor for linear movement, (2) motor for ankle dorsiflexion/plantarflexion, and (3) force sensor.



(**a**) (**b**)

Figure 2. The prototype of the lower-limb therapy device on a medical bed (**a**) and with a test person (**b**): (1) touch screen, (2) emergency stop, (3) foot plate, and (4) force sensor.

A 4-axis hardware motion controller (MiniMACS 50/10, maxon motor, Sachseln, Switzerland) was used in this study to control movement. Position and force control algorithms were developed in ApossIDE (Version 7.00, maxon motor, Sachseln, Switzerland). The device offers three training patterns: (1) passive ankle dorsiflexion/plantarflexion; (2) passive linear foot training with synchronised ankle movement; and (3) active leg pressing.

2.2. Movement Control Strategies

In order to produce the three types of training described above, the algorithms for passive position (Figure 3a) and active force (Figure 3b) control were developed. In passive mode, the target trajectories for the ankle dorsiflexion/plantarflexion and linear placement were given. The four motors were set to run in speed mode. The PID position controllers that were embedded in the motion controller were implemented in the four motors to produce the target trajectories. The transfer function of the controller is as follows:

$$C_{PID} = k_{\mathrm{P}} + \frac{k_{\mathrm{I}}}{s} + \frac{k_{\mathrm{D}} s}{\frac{1}{\omega_{lp}} s + 1} \quad (1)$$

where k_{P}, k_{I}, and k_{D} are the proportional, integral, and derivative gains, respectively. A low-pass filter was implemented for the derivative term, where the cut-off frequency ω_{lp} = 1000 Hz. The actual linear movement and ankle rotation were measured via the encoder on the motors. These position measurements were calibrated. There were limit switches on both ends of the linear movement.

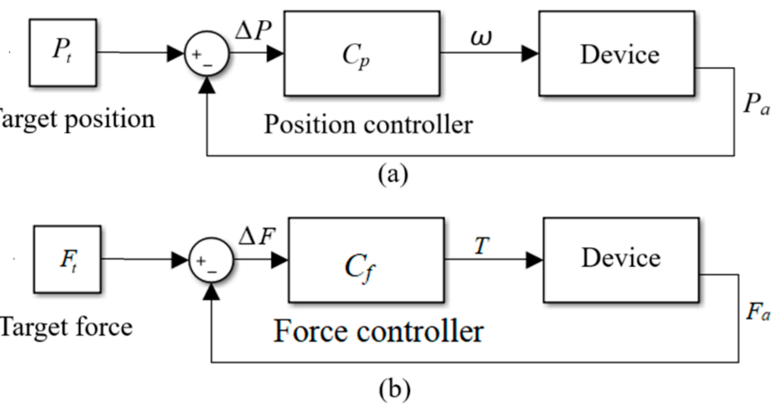


Figure 3. Control algorithms. (**a**) Position control. (**b**) Force control.

In order to produce active training, the force control strategy (Figure 3b) was implemented in the two motors with the screw drives to produce active loading during leg pressing. The motors were set to run in torque mode, and a PID force controller with the same transfer function as in Equation (1) was employed. The other two motors for ankle rotation were blocked, operating in passive position mode, with a constant ankle position of 0° set as the target position.

Using the Scope function in ApossIDE, the parameters of the three PID controllers were tuned based on the experimental trial-and-error method [14]. The integral and derivative gains k_I and k_D were initially set as zero, while the proportional gain k_P was gradually increased so that the actual position or force tracked the step response with acceptable performance (rising time shorter than 0.5 s; tracking error smaller than 5%). Then, the integral and derivative gains k_I and k_D were slightly tuned to refine the movement.

2.3. System Programme Architecture

In order to provide easy operation for the users, i.e., physiotherapists and patients, a touch screen (Figure 2) with an embedded system programme on Raspberry Pi was used. The primary software for the system was developed in PyCharm (Version 2023.3.4, JetBrains, Prague, Czechia). The Integrated Development Environment facilitated the development of the main application in Python. Additionally, Visual Studio Code (Version 1.91, Microsoft, Redmond, WA, USA) was used to directly programm on Raspberry Pi.

The programme was divided into two main components (Figure 4). Its architecture was designed to ensure that communication was initiated and controlled by the main programme through queries and the continuous transmission of commands. The scripts Firmware.mc, Motion.mh, Can.mh, Init.mh, and Param.mh operated on the standalone MiniMACS controller. This configuration facilitated the automatic start function and initialised the PID control parameters for both position and force controllers. In contrast, the scripts “Execute”, “Hosting”, “Controller”, and “Data” were executed on Raspberry Pi. CAN communication (red dotted line in Figure 4) between the Raspberry Pi and the MiniMACS was facilitated by both the Can.mh script on the MiniMACS and the “Controller” script on Raspberry Pi. The “Hosting” script utilised the “nicegui” library, employing its tools and building blocks to provide a comprehensive user interface (Figure 5) and establish connections to the implemented exergames (see Section 2.4). All data and overarching variables were securely stored within the “Data” script.

Regarding the user interface, three pages were created: Testing (Figure 5a), Computer Game (Figure 5b), and Data (Figure 5c). On the Testing page, tabs were created for the calibration of force and encoder sensors, initial movement testing, and motor mode selection. On the Computer Game page, several games could be selected. On the Data page, there were graphs to monitor the data and buttons to save or delete training data (Figure 5c). The user interface allowed the user to start/stop the system, set target force position profiles, and view the training results. The results, such as the target/actual force and position of the foot plates and the motor torque, were saved using the “Data” package.

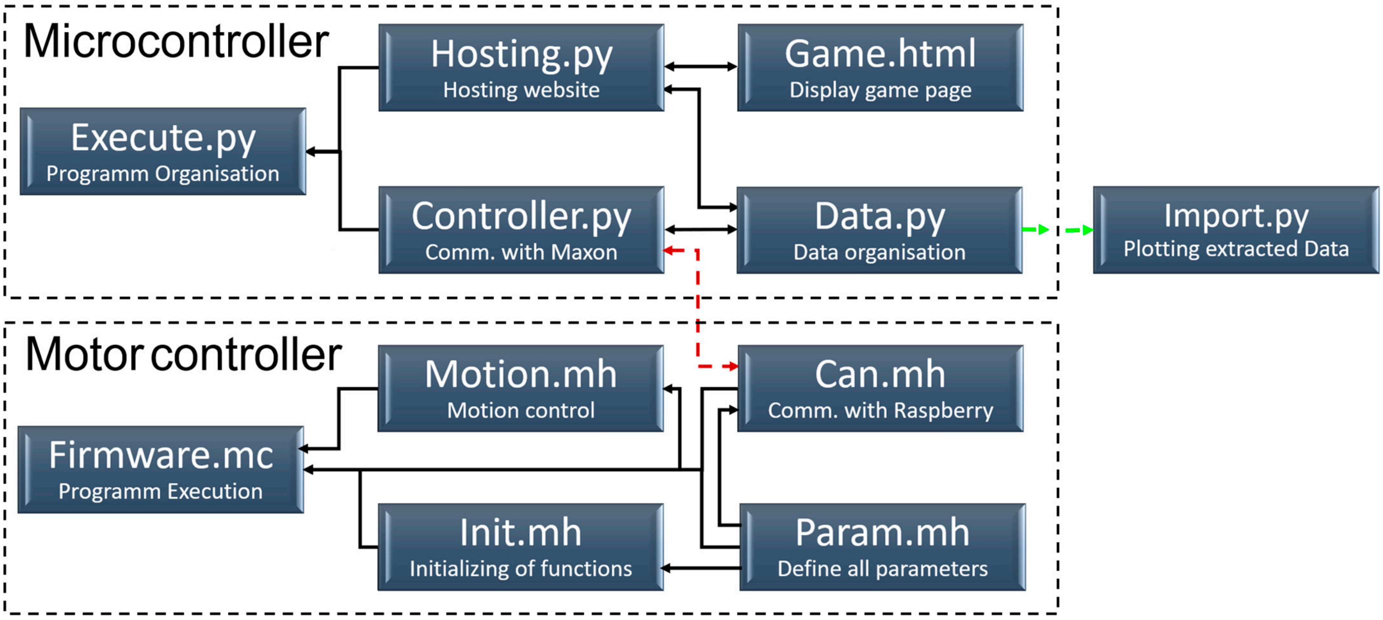


Figure 4. System programming architecture. The red dotted line means communication between the Microcontroller and the Motor controller. The green dotted line indicates data export and transport using a USB-Key.

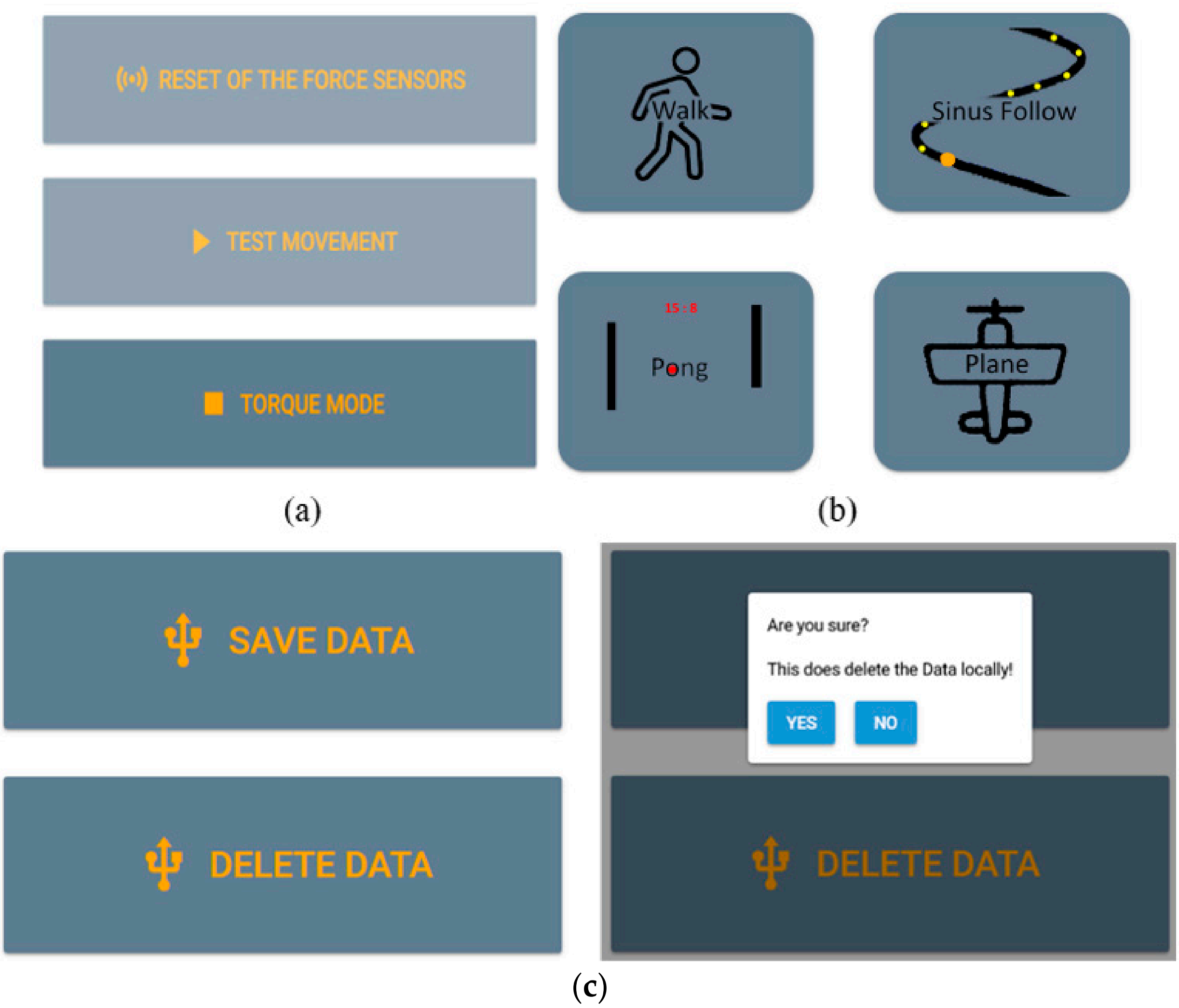


Figure 5. The pages for the user interface: (**a**) Testing, (**b**) Computer Game, and (**c**) Data.

2.4. Development of the Computer Games

To encourage users to actively participate in training, computer games (Figure 5b) were incorporated into the training programme. The exercise games were developed through the employment of the Godot Engine (Godot 4, Godot). It synchronised the leg movement with the animation of the games. The movement path was predefined in the computer game engine. The moving object could be controlled by pressing the right or left foot plates with a certain displacement. The linear position difference between both feet was sent to the computer games to define the position of the moving point.

During training with the exergames, the force control strategy shown in Figure 3b was implemented on both legs. As shown in a computer game example of a sinusoidal curve, the target force and the moving speed of the simulation point were defined (Figure 6a). The main task of the game is to control the yellow circle to collect coins that are scattered on the path (Figure 6b). The participant interacted with the computer game by moving their legs so that the movement followed the defined path on the screen.

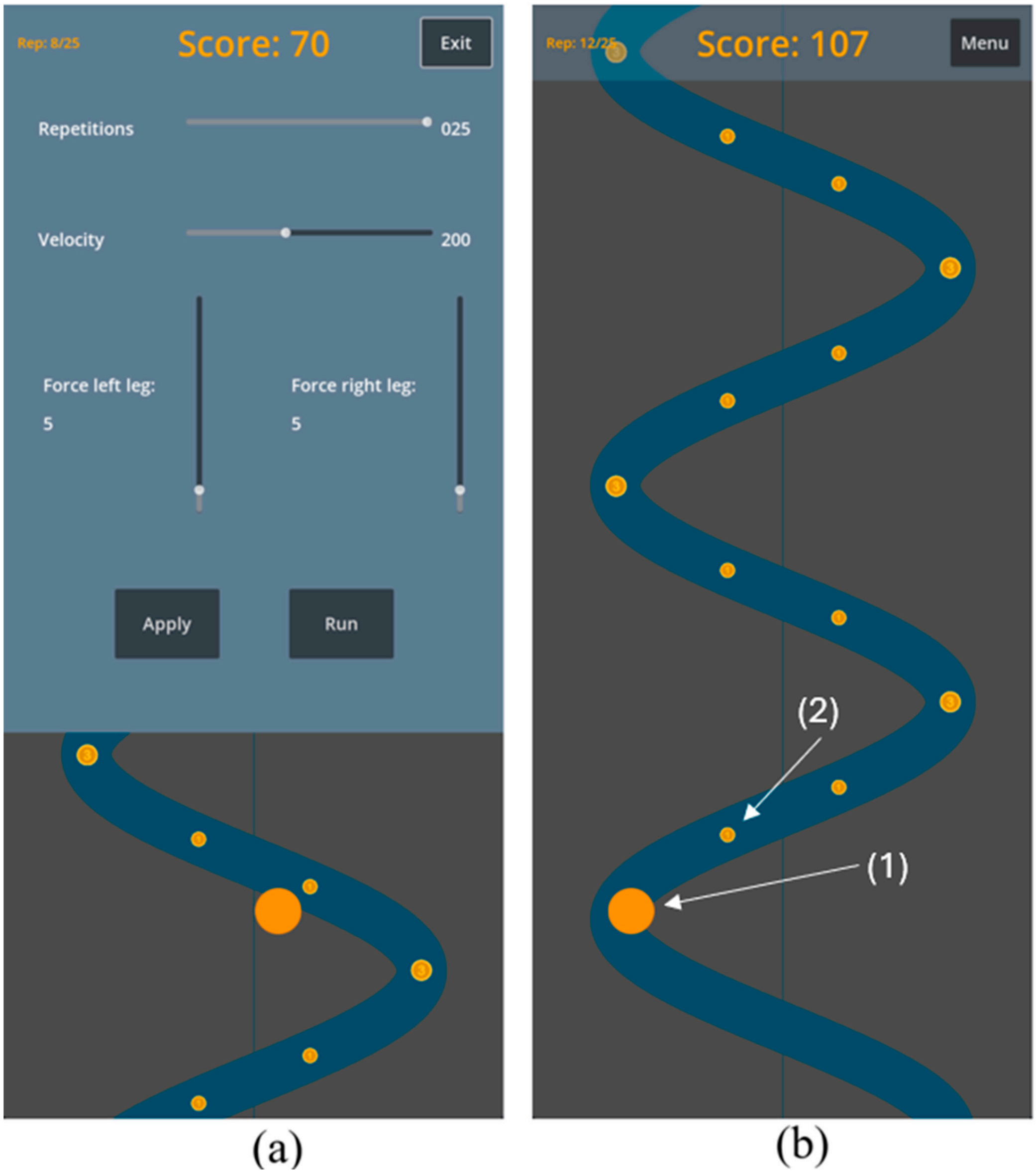


Figure 6. An example of the computer game's sinusoidal curve: (**a**) game setup, and (**b**) computer game shown on the touch screen. (1) Moving point and (2) coin.

2.5. Evaluation Test

In order to evaluate the technical functionality, a test was carried out with 12 able-bodied participants (mean age 32.5 years, mean height 1.80 m, Table 1). They were recruited using convenient sampling primarily from the involved educational institutions, i.e., the students, assistants, and researchers of the rehaLab. The study did not fall under the Swiss Human Research Act because it did not investigate human pathology or physiology, nor did it involve the collection of health-related data [15]. Therefore, no ethical approval was required.

Table 1. Participant information.

	Age (Years)	**Body Mass (kg)**	**Height (m)**
P1	27	83	1.73
P2	22	62	1.65
P3	39	76	1.81
P4	42	80	1.93
P5	24	82	1.78
p6	26	113	1.92
p7	33	63	1.72
p8	30	75	1.80
p9	61	78	1.85
P10	29	64	1.70
P11	28	82	1.83
P12	29	86	1.89
Mean	32.5	78.67	1.80
STD	10.66	13.6	0.089

STD: standard deviation.

The therapy bed was stablised by four brakes. The participants were positioned on the bed in a recumbent posture, with their feet fixed on the foot plates of the device. First, they familiarised themselves with the functions of the device. Then, they rested for one minute before starting the formal test. Three sessions were tested: passive, active, and game sessions. Each session consisted of 10 reciprocal leg movements and was repeated three times. The break between each repetition was approximately 30 s. In the passive session, the participant followed the movement produced by the foot platforms. The target movements were sinusoidal positions in the linear axis and the rotational ankle joint. The movement had a range of 250 mm displacement and 26° rotation in the ankle joint. In the active session, the participant pressed against the foot platforms in order to stretch both legs reciprocally. They moved to the beat of a metronome, which was set to 20 beats per minute for all participants. In the game session, the participant pressed against the foot platforms and moved both feet in order to follow the trajectory path shown in the computer game and collect as many coins as possible. During the active and game sessions, a target force of 50 N was defined for each foot. A video of the game session was provided in the Supplementary Materials to show how the device and the participant's limbs were oriented during the tests.

After the participant finished the test, they filled out a questionnaire. Thirteen questions were prepared based on a modified System Usability Scale [16]. Seven of them were related to mechanics and movement control, which are based on whether:

(1.1) The participant liked the appearance;
(1.2) The participant had a positive impression of the overall device;
(1.3) The participant found it convenient to transport the device;
(1.4) The participant found the device easy to use;
(1.5) The participant was happy about the interaction/reaction speed during use;

(1.6) The participant was comfortable with the force intensity during the exercise;
(1.7) The participant felt physically good while and after exercising with the device.

The other six questions were related to the user interface and computer game, which are based on whether:

(2.1) The game was engaging and kept their interest throughout training;
(2.2) The training using the game was more exciting than the one without the game;
(2.3) The game ran smoothly with acceptable delay;
(2.4) The user interface was clear and easy to navigate;
(2.5) The test results gave you a strong sense of achievement;
(2.6) The participant would recommend this device to their friends.

A qualitative analysis was performed using the evaluation method proposed in [16]. The answers to the questions were analysed on a scale of 5, where "1" to "5" means "strongly disagree", "disagree", "neutral", "agree", and "strongly agree", respectively.

The movement data of each session were analysed. The accuracy of force control was calculated using the root-mean-square error (RMSE) between the target force F_t and the actual force F_a:

$$\mathrm{RMSE}_F = \sqrt{\frac{1}{N}\sum_{t=t_0}^{t_1} (F_{\mathrm{a}}(t) - F_{\mathrm{t}}(t))^2}, \tag{2}$$

where N is the number of data points in the interval t_0 and t_1. Replacing the force with positions in Equation (2), the accuracies of position control of the four motors were calculated.

3. Results

The passive mode was tested with the target positions for both legs as the sinusoidal trajectories (Figure 7). The PID controller parameters for the linear motors were k_P = 40, k_I = 0.25, and k_D = 400. Regarding the motors for ankle rotation, the PID parameters were k_P = 15, k_I = 0.25, and k_D = 25. The position control accuracies from a representative participant (P5) were 10.87 mm for linear movement (Figure 7a,b) and 1.28° for the ankle joint (Figure 7c,d). P5 was selected because its results were close to the overall mean results (Table 2).

Table 2. RMSE in movement control.

	Linear Position (mm)	Ankle Joint (°)	Force (N)
P1	10.40	2.22	1.57
P2	6.82	1.24	2.45
P3	5.48	1.52	2.12
P4	8.66	3.59	2.82
P5	10.87	1.28	2.57
p6	7.04	1.81	2.08
p7	8.11	0.85	1.95
p8	12.98	1.30	2.31
p9	4.99	0.79	2.38
P10	5.15	0.80	2.27
P11	9.71	2.86	4.20
P12	16.69	1.21	3.56
Mean	8.91	1.62	2.52
STD	3.49	0.87	0.72

STD: standard deviation.

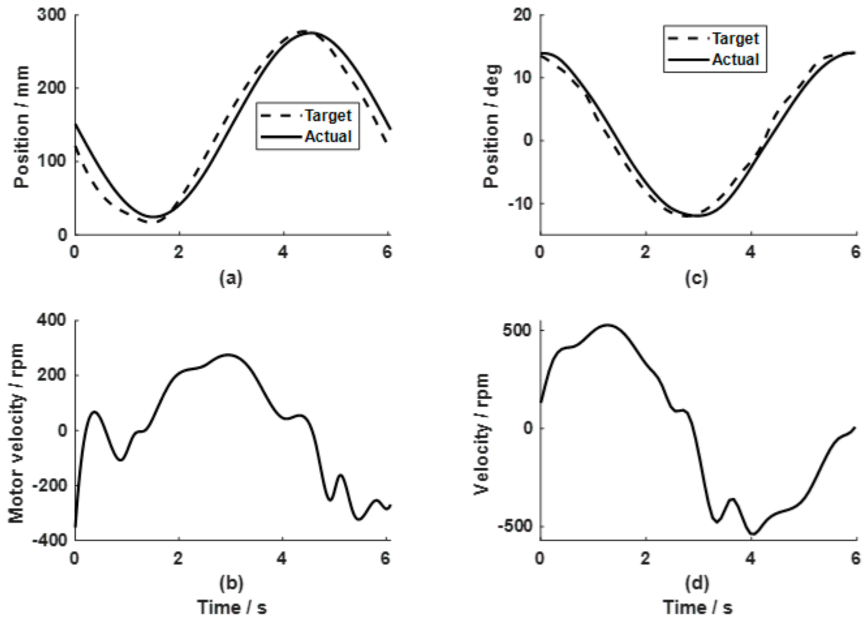


Figure 7. Passive position control of the right leg of a representative participant (P5). (**a**,**b**) the position of the foot platform and the motor velocity to produce the linear movement. (**c**,**d**) the position of the ankle joint and the motor velocity to produce dorsiflexion/plantarflexion.

In the active mode (Figure 8), the control parameters for the two linear actuators were tuned to be $k_P = 1.5$, $k_I = 0.25$, and $k_D = 0.05$. The force control error of the representative participant was 2.57 N. The error mainly came from the linear movement of the leg. During the test, leg movement varied in a range of 10–290 mm (Figure 8c), where the actual range of movement was voluntarily controlled by the individual participant.

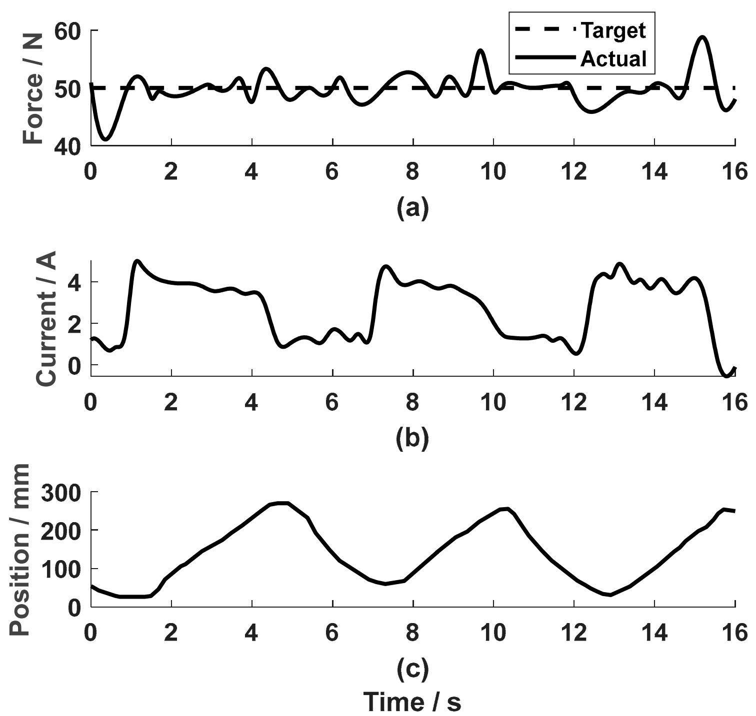


Figure 8. Force control of the active load on the right leg of the representative participant (P5). (**a**–**c**) are the force, motor current and the linear movement during the active training.

To summarise the test results of the 12 participants (Table 2), the position control error for the linear position was 8.91 ± 3.49 mm, and for ankle joint rotation, it was 1.62 ± 0.87°. The force control accuracy was 2.52 ± 0.72 N.

All participants completed the questionnaire (Tables 3 and 4). Regarding the mechanics and movement control, all participants agreed or strongly agreed that they liked the appearance (Q1.1) and felt comfortable with the force intensity during the exercise (Q1.6). 11 participants agreed or strongly agreed that they obtained a positive impression of the overall device (Q1.2). Ten participants agreed or strongly agreed that they felt physically good while and after exercising with the device (Q1.7). Only one participant (P4, a body-height of 1.93 m) disagreed regarding physical feeling from usage of the device. He commented that the training bed was too short, which allows a length of 0.86 m for leg movement. Nine participants agreed or strongly agreed that the device was easy to use (Q1.4). Regarding the computer game, 11 participants agreed or strongly agreed that the game was engaging and kept their interest throughout (Q2.1), and the training using the game was more exciting than the one without the game (Q2.2). Eight participants thought the user interface was clear and easy to navigate (Q2.4), while the remaining four participants were neutral to this statement and commented that a user manual page or an introduction would be desirable.

Table 3. Answers to questions about mechanics and movement control.

	Q(1.1)	**Q(1.2)**	**Q(1.3)**	**Q(1.4)**	**Q(1.5)**	**Q(1.6)**	**Q(1.7)**
P1	4	4	2	3	3	4	3
P2	4	5	2	4	2	4	5
P3	5	4	5	5	5	4	4
P4	4	3	2	3	2	5	2
P5	5	5	4	4	3	4	4
p6	5	4	4	4	3	5	5
p7	4	4	3	4	3	4	4
p8	5	4	4	5	4	4	5
p9	4	4	5	5	4	4	4
P10	4	5	4	5	4	5	5
P11	4	4	2	4	3	4	4
P12	4	4	4	3	5	5	5
Mean	4.33	4.17	3.42	4.08	3.4	4.33	4.17
STD	0.49	0.57	1.16	0.79	0.99	0.49	0.94

STD: standard deviation.

Table 4. Answers to questions about the user interface and computer game.

	Q(2.1)	**Q(2.2)**	**Q(2.3)**	**Q(2.4)**	**Q(2.5)**	**Q(2.6)**
P1	5	5	2	3	3	4
P2	5	5	2	3	5	5
P3	4	5	4	4	5	4
P4	4	5	4	3	3	3
P5	3	5	2	4	4	5
p6	5	5	2	4	5	5
p7	4	5	2	4	3	4
p8	5	5	2	4	4	5
p9	4	4	4	4	4	4
P10	5	4	3	5	5	5
P11	4	5	3	4	4	3
P12	4	3	4	3	4	4
Mean	4.33	4.67	2.83	3.75	4.08	4.25
STD	0.65	0.65	0.94	0.62	0.79	0.75

STD: standard deviation.

A System Usability Scale score of 70%, or 3.5 out of 5 points, indicates good usability, while 4.0 out of 5 points means excellent usability [16]. Summarising the questionnaire results of the 12 participants (Tables 3 and 4), a mean score higher than 4.0 points was obtained in five out of seven questions regarding the mechanics and movement control yield, and four out of six questions related to the user interface and computer game. Therefore, the usability of the in-bed lower-limb therapy device was rated as excellent apart from Q1.3, Q1.5, and Q2.3. Four participants disagreed with the statement that the device was convenient to transport (Q1.3) due to the weight of the device (approximately 18 kg). A trolley or an automatic cart was recommended. Only five participants agreed or strongly agreed that they were happy about the interaction/reaction speed during use (Q1.5). This feedback was related to Q2.3, where six participants commented on the long delay between the simulated movement of the yellow point and the actual leg movement. Nevertheless, nine participants agreed or strongly agreed that the test results produced a strong sense of achievement (Q2.5). Ten participants wanted to recommend the device to their friends (Q2.6). One felt that the system reaction speed needed to be improved before a recommendation could be made, while the other wanted to recommend a lighter system for the sake of easy transport.

4. Discussion

To prevent prolonged inactivity, a robotic device to facilitate early mobilisation is desirable. The first iteration of a User-Centred Design process [6] resulted in clear user requirements for such a robotic device. This work developed and evaluated the usability of a prototype in-bed lower-limb therapy device that offers various training patterns for the feet and legs, featuring an intuitive user interface and interactive exergames. Four motors produced bilateral leg pressing with synchronised ankle dorsiflexion/plantarflexion. Using the touch screen, the system was operated conveniently to provide passive training with a user-defined range of movement and active training with a computer game. Preliminary testing on 12 able-bodied participants showed that the system produced training with acceptable accuracy. The user interface with the interactive computer game was found to be technically implementable and usable. Future work includes improving the control strategy, increasing the reaction speed of the computer game, and conducting clinical studies for evaluation of the feasibility and effectiveness of the developed system.

This study reports on a compact standalone device, which could easily be operated to provide training on the bilateral legs and ankle joints for bed-resting users. Passive position control is an important training mode for vulnerable users during the bed-resting phase. The position control algorithms enabled the device to produce acceptable results in passive mode. The ankle joint is important in daily living and sports activities [17]. It stabilises the leg and provides dynamic energy for the lower limb to interact with the ground. A fit and powerful ankle joint is crucial for normal gait [18]. Therefore, the generation of plantarflexion/dorsiflexion training was deemed a desirable function of the device. Unlike our first pneumatic model [13], the current device uses electric motors to produce the required movement. Actuation of the legs and ankle joints requires two linear and two rotary drives. The advanced motion controller, MiniMACS, enables simultaneous control of four motors, resulting in a compact control system for the lower-limb therapy device. Participant feedback showed that they generally liked the device's appearance and were satisfied with its performance.

The force control algorithms yielded satisfactory results in active mode, but better control strategies will be explored. To ensure effective training, physical guidance should be adapted to varying needs as training progresses [12,19]. After a period of passive training, users may obtain some recovery of voluntary control, necessitating active training with resistance on the lower limbs. Due to the limited control blocks provided by the ApossIDE library, the current study used the PID control strategy that was embedded in the motion controller. Using experimentally tuned parameters, the PID controllers produced acceptable movement accuracy (Figures 7 and 8 and Table 2). However, there is room for improvement in the control algorithms. The software ApossIDE also supports self-developed blocks for motor control. Movement control can be improved by implementing controllers designed with the pole-assignment approach [20]. Additionally, test results indicated that force control accuracy was influenced by the voluntary movement of the foot platform. Velocity disturbances are a common issue in force control [21]. This test implemented force at a fixed speed (metronome of 20 BPM). If the metronome beat is higher, the test person will physically move their feet at a higher speed, resulting in a higher influence of movement speed in force control accuracy. The force control strategy of the lower-limb therapy device can be improved by integrating a feedforward velocity compensator. These control strategies will be explored in future research.

The computer game was found to be interesting and intuitive. Its strengths included ease of operation and functionality to encourage active participation throughout training. Various approaches exist for developing computer games, such as using a head-mounted display [22] or the Unity 3D game engine [23], which often involve many cables and/or require a powerful computer. However, interviews with physiotherapists [6] showed that the device should be easy to set up and operate. Therefore, a standalone platform using Raspberry Pi was selected, which enabled convenient operation via a touch screen. The interactive computer game motivated the test participants during training, and the user interface graphically displayed the training results. Biofeedback and computer games can potentially be viewed through smartphones. Testing with participants showed that the user interface was intuitive to navigate, and the interactive computer game effectively engaged them during training. Nevertheless, the current exergame has a limitation: a delay between the actual and simulated movements in the game. During the test, half of the participants felt that the simulated movement was too delayed compared to the actual movement. To address this, a more powerful microcomputer will be investigated in the future.

In addition to validating the device's technical feasibility, the preliminary test shows areas for improvement. The prototype should be enhanced from both the operators' and participants' perspectives. Four participants expressed concerns about the ease of transferring the device. This is understandable given the device's weight of approximately 18 kg. Some participants noted that the foot platform moved during foot strapping in the user setup phase. To address this, a strap-in mode could be programmed to hold the foot platforms in place. These findings show the need for adjustments in the mechanical design and system programme to enhance user satisfaction and operational comfort.

5. Conclusions

Following the User-Centred Design process, we developed a compact in-bed lower-limb therapy device with interactive exergames. Automatic position and force control strategies enabled the device to provide leg flexion/extension with synchronised ankle plantarflexion/dorsiflexion, as well as linear leg pressing with adjustable resistive loading. Preliminary tests proved the acceptability and usability of the device in terms of mechatronics, movement control, user interface, and the computer game. The technical advancements of the therapy device include well-controlled movement, multi-modal training patterns, convenient operation, and interactive exergames. As a system for early mobilisation, the therapy device shows potential to improve not only physical activity but also cognitive functionality for users during the bed-rest phase.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/act14020060/s1. Video S1: Physical training with a computer game.

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