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Article

Development of Immersive VR Device for Gait Training Rehabilitation with Biofeedback System-Preliminary Study

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Abstract: Gait-training rehabilitation machines (MGTR) are contraptions used for the motor rehabilitation of patients with movement disorders resulting from stroke and Parkinson's disease. This study was aimed at implementing a walking pattern similar to the normal gait. Background: Immersion and motivation are important factors in repetitive rehabilitation exercises. This was addressed by synchronizing walking speed and virtual reality (VR) visons to provide a sense of immersion in a convergence environment of MGTR and VR. Methods: The difference in joint angle and gait event was confirmed when the step length was adjusted in this system to control the joint movement. Results: It was confirmed that the joint range of motion also increased significantly as the step length increased. Conclusions: The possibility of developing a more immersive MGTR system that feedback the actual gait state in the VR system was confirmed by applying that the joint movement varies according to the step length. It will be possible to provide an immersive feeling more similar to the actual walking by modifying the gait trajectory of the MGTR.

Keywords: gait rehabilitation; virtual reality; joint angle; step length; robot

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1. Introduction

The occurrence of patients who have survived brain injury or undergone lower-extremity joint surgery is rapidly increasing due to aging, accidents, and stress. Rehabilitative training for such patients is vital, with gait training being the most essential form of such rehabilitation [1]. Gait training and rehabilitation focusses on strengthening and restoring intrinsic motor functions with exercises to enhance skeletal movement, along with muscle contraction and relaxation, within the normal range of motion (ROM) of the joint [2]. Additionally, the market for gait rehabilitation devices is rapidly expanding. In preparation for this trend, it is necessary to develop an effective, inexpensive device so that it can be widely used in gait rehabilitation [3].

The most important factor in gait rehabilitation training machines (MGTRs) is the implementation of a normal gait pattern [4]. These devices exist as two types: exoskeletal and end-effector. The exoskeletal type consists of three actuators—one each on the hip, knee, and ankle—that control the movement of the entire joint, while the end-effector type controls joint movement by adjusting the shape of the sole when it touches the ground [5]. Gait rehabilitation aims to realize the form of normal gait, and the effects recreated by both types of devices are very similar to those of normal gait [6,7].

MGTR systems assist patients with gait disorders (such as stroke and Parkinson's) by helping them develop gaits that are similar to the normal gait; this improves their brain plasticity and muscular activity while reducing imbalance [8]. However, patients face problems such as boredom and familiarity while undergoing repetitive rehabilitation exercises; this leads to a decrease in their immersion and motivation, which impairs their rehabilitation [9]. Therefore, a patient's immersion, motivation, and sense of achievement with the rehabilitation exercise strongly influence the success of said exercise [10]. This brings to light the need for technologies that enable cognitive immersion during rehabilitation exercises to motivate patients and provide them with a sense of achievement; virtual reality (VR) technology is one such element [11,12]. VR provides users with a simulated experience (that can be as similar to, or different from, their actual environment as required) in a virtual visual setting. Immersion is generally provided by synchronizing this setting with the user's visual and motor movements, with sensory feedback provided by a haptic device [13].

VR provides a simulated environment with essential feedback for learning and motivation; this has enabled its use in several real-world scenarios [14]. It goes beyond the limits of a system that provides only visual feedback in a simple static state, and instead synchronizes with the dynamic changes in a user's surroundings to provide them with a sense of immersion. It can also solve the spatial and safety problems that occur during gait rehabilitation. In addition, it also helps measure (and biomechanically analyze) user gait, enabling an awareness and sharing of it between patients, therapists, and doctors [15].

The effect of rehabilitation treatment is enhanced by the convergence of the MGTR and VR systems. When MGTR and VR trainings were provided as interventions for 24 children with neurological gait disorders, the stance and swing phases of their gaits were significantly improved compared to the results achieved from the exercise and image therapy provided by their therapist [16]. In addition, it was confirmed that motivation increase, perceived pressure and emotional strain decreased when the MGTR was implemented along with VR for 20 subacute stroke patients [17].

As such, VR-MGTR convergence requires a biofeedback system that feeds back the gait state in real time; this enhances rehabilitation when compared to exercising without VR (Weber (2020)). Walking speed is a basic element indicating the state of gait; its measurement is necessary to adjust step length while walking, which maximizes immersion and rehabilitation through VR synchronization [18,19].

In this study, a system with a five-bar link structure was developed to overcome difficulties faced in realizing a normal gait pattern and joint position trajectory, which are limitations of the end-effector type of MGTR. A biofeedback system was also applied to this structure to automatically adjust step length by measuring the walking speed in real time; this enhanced the functioning of the MGTR by synchronizing the actual walking speed of the patient with the VR system. The assist control factors of the MGTR were also determined by analyzing the variation of patient gait with step length.

2. Methods

2.1. MGTR Design

The MGTR system comprised a gait trajectory driver and a VR head-mount display (HMD) system to kinematically implement the gait form of stroke patients (Figure 1). An open backside provided easy access to patients using wheelchairs, while the handle bar was designed to make it easier to rise from the seated position and get reseated. An easily-attachable harness system was also included to prevent falls [20].

2.2. Mechanism of Gait Functionality

The MGTR design was of an end-effector type, implementing the gait trajectory through the foot. It generates movement at the ankle by arranging it on a five-bar link, using it to induce flexion and extension around the knee and hip joints [20]. A flywheel was used to ensure the stable and continuous operation of the link structure, designed to enable symmetrical movement on the left and right sides. An electric stepper motor was connected to the center of rotation of the flywheel and driven. The foot step comprised of several rollers so that when the foot fixing unit came in contact with them, rollers at both ends of the step could rotate; this assisted the patient in walking. To ensure safety, the foot anchor used was of the binding-type (Figure 2).

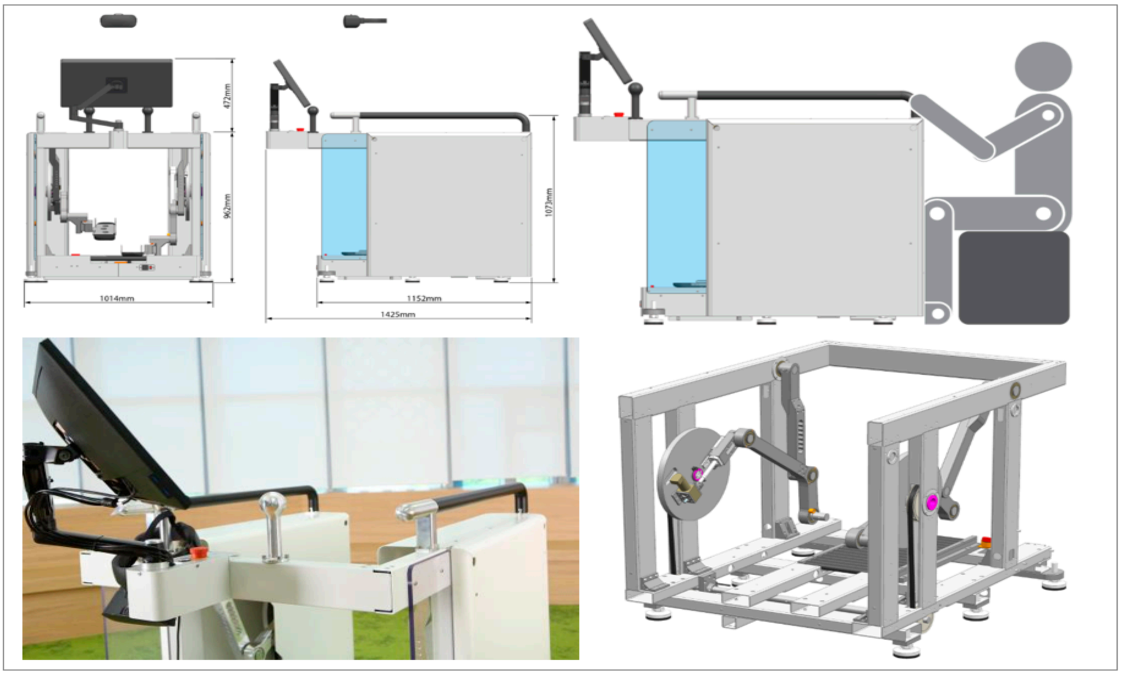

Figure 1. MGTR design.

Figure 2. Mechanism of gait functionality.

In general, the walking speed increased with step length [21]. Variables such as speed and step length were reflected in the VR character's movements, synchronizing the movements of the user and VR character so that the patient could focus on the rehabilitation training.

The operation diagram of the whole system is shown in Figure 3. When AC power of 220 volts is applied, power is divided from an AC switch and input into computer, switching mode power supply, monitor and VR head mount display device. Switching mode power supply is input to the main PCB, DC motor, and BLDC motor as 24 volts DC. The main PCB communicates the data of the rotary encoder, and the DC motor driver controls the step length and magnetic brake. The BLDC motor driver transmits mechanical power to the lower limb crank axis and links.

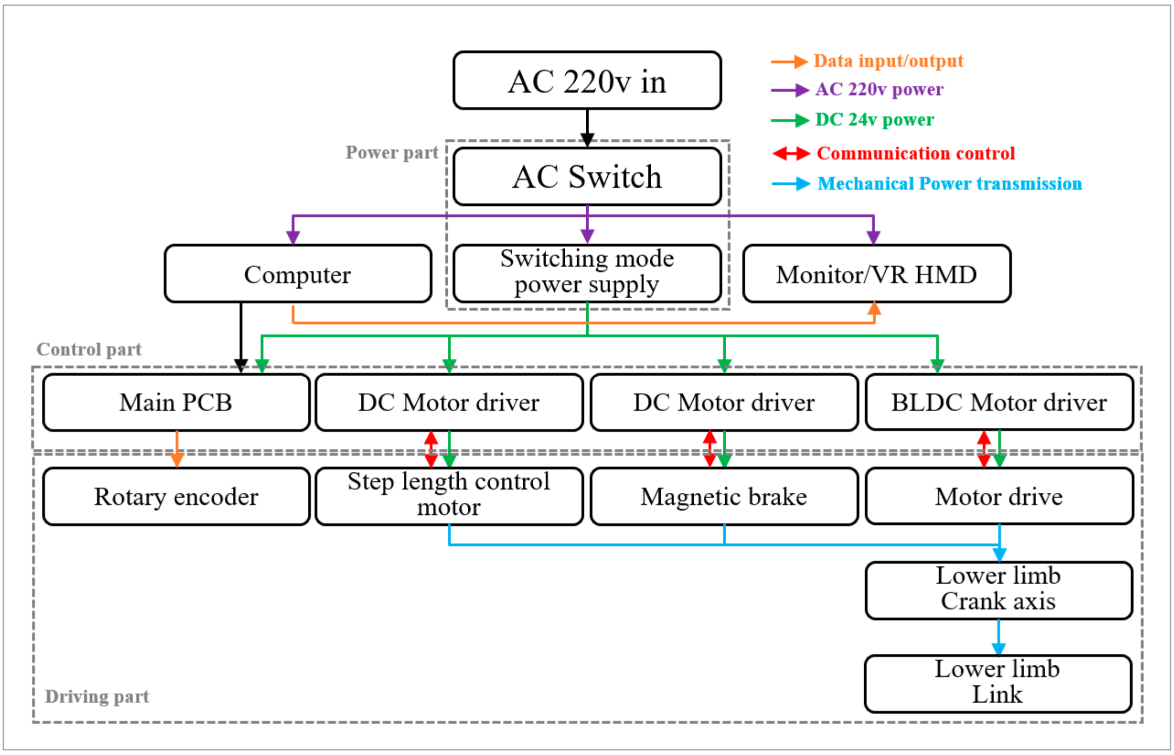

Figure 3. Block diagram of MGTR system operation.

To enable step-length adjustment with walking speed, a system was constructed to detect the walking speed. Using an LED photo-interrupter, the linked arm measured the speed at which the emitted light was interrupted during the spinning of the flywheel. This measurement was made through a continuously detected delay—if the calculated walking speed increased from the initial value, the length of the link (in the form of a screw) was adjusted in real time to decrease the step length; if the speed decreased, on the other hand, step length was increased by adjusting the length of the link. This was used to enhance the immersive component of the exercise in a VR environment by adjusting the step length according to the speed. The flow chart of the system and the driving algorithm for step control are shown in Figure 4.

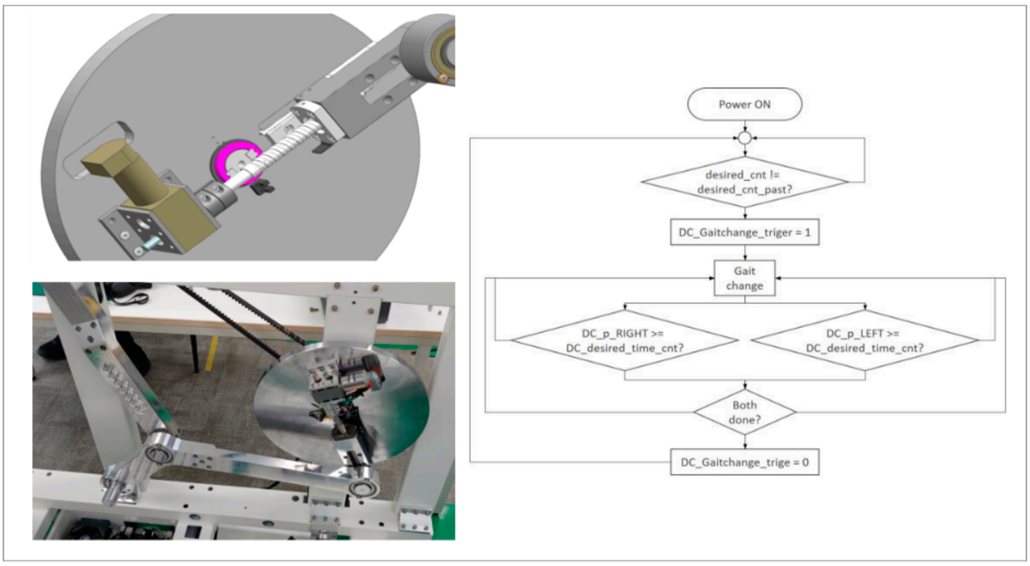

Figure 4. Step length control system algorithm.

2.3. Application of VR System

On boarding the MGTR, attributes, such as speed and step length, were immediately reflected in the movement of the VR character in a way that matched the movement of the user, thereby enhancing user immersion in the experience. A magnetic brake was used to control the speed. The actual walking speed was streamed to the VR system, which was in turn linked to a VR track game designed as a running track. During training, gait measurement data such as speed, usage time, power assist level, and asymmetry of the centers of gravity of the left and right feet were transmitted to the PC (Figure 5).

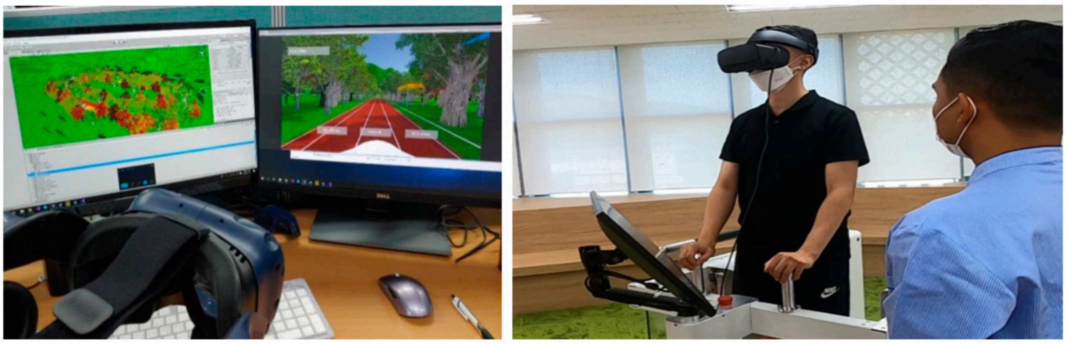

Figure 5. Application of VR system.

2.4. Training Program

The MGTR training program consisted of passive, active, and active-assisted modes. When the program was executed, the mode was selected after user registration. After boarding, the user was asked to participate in the VR track game. When training starts, the step length is adjusted by detecting the speed of walking in the active-assist mode. During training, record asymmetric, stride, step condition, distance, and speed of the left and right legs. Additionally, once they were finished, their scores were calculated based on the walking speed, number of repetitions, distance, and movements of the centers of gravity of both feet (Figures 6 and 7).

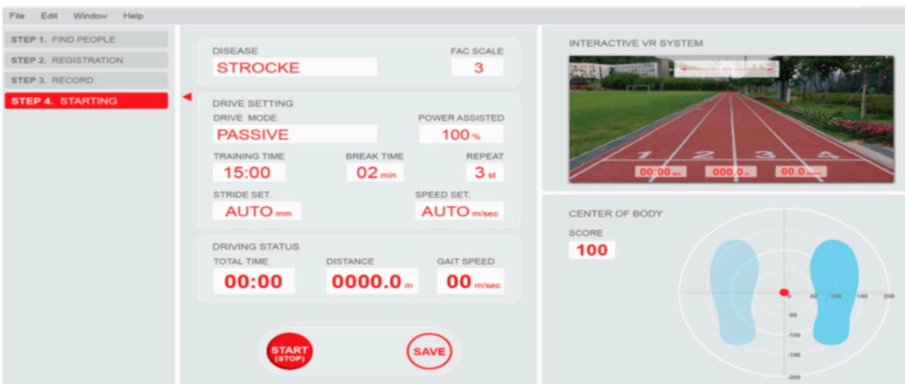

Figure 6. MGTR training program.

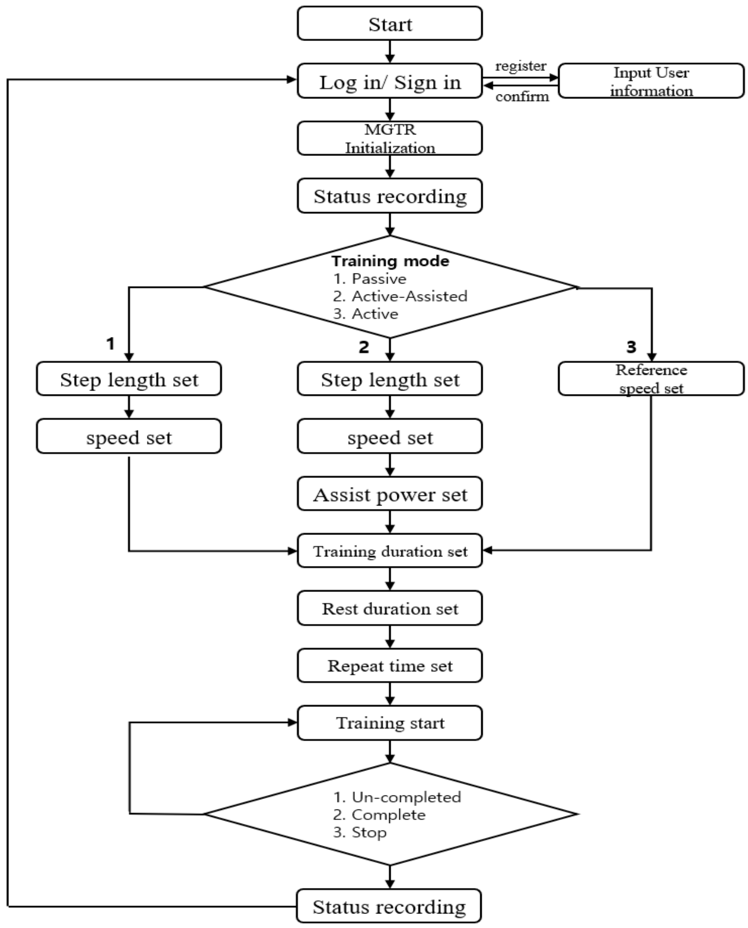

Figure 7. MGTR training program block diagram.

2.5. System Functioning Test

Attributes of the finished product, such as the maximum allowable load, stability, durability, and noise, were determined through tests. The maximum allowable load was measured according to the standard that can withstand four times the maximum user weight of 100 kg. First, a balance was placed on one side of the step plate, and a load of 400 kg was applied for 5 min. To evaluate stability, a subject (with a height and weight of 175 cm and 100 kg) boarded the contraption and operated it at a speed of 60 beats per minute, during which the inclination of the instrument was evaluated. within 10° forward and backward and 5° in the lateral direction. To evaluate durability, a load of 50 kg was applied to each of the two-step plates, and 100,000 cycles were performed at a rate of 60 cycles per minute. After this, the load was removed and the contraption was examined for any damages. To determine the noise generated, a decibel noise meter was used to measure the noises generated at distances of one meter from the front, rear, left, and right sides of the MGTR during its regular operation.

2.6. VR System Test

A calibrated protractor was placed on a paper, using which reference lines of 0°, 45°, 90°, 135°, and 180° were drawn to check the accuracy of the VR device. The VR device was positioned parallel to the MGTR. The error range between the yaw angle measured by the VR device and the angle reference line drawn with the protractor was compared.

To check the VR reaction speed, the time at which the serial signal was sent to the micro-controller unit (MCU) using the terminal program of the operating software was first record. The signal received by the MCU was transmitted first to the operating program and then to the VR program, and the time at which the signal was received at both programs was recorded. The difference in the reception time between the two programs was then checked to see if it was performed within 60 ms.

The VR resolution was determined by recording the time taken for each screen update of the operating program and the VR program. When the save button was pressed after executing the terminal part of the operating program, the screen update data recorded by the operating and VR programs were checked and the time recorded was determined in seconds.

2.7. Kinematic Evaluation

During the development stage of the MGTR, a simplified experiment was performed to check its driving state while boarding. The variation of joint angle with step length was determined and five male subjects (age: 25 ± 3.8 years, height: 173 ± 2.5 cm, weight: 72 ± 4.2 kg) were subjected to kinematic evaluation when walking on the MGTR. The device was operated in the active-assisted mode, a state in which the motor intervenes on detecting movements indicating an intention to walk. Walking speed was fixed at 1.0 km/h and motion analysis was performed with a motion capture system (Prime 13, OptiTrack Inc. Corvallis, OR, USA) consisting of four 3D infrared motion capture optic cameras. Reflective markers were attached to the Helen Hayes marker set and the gait event, joint angle, joint ROM, and gait speed were all calculated for step lengths of 310, 350, 390, and 430 mm. STT InSight Motive (ver.2019.1), manufactured by STT Systems Inc., San Sebastián, Spain, was used for data analysis (Figure 8).

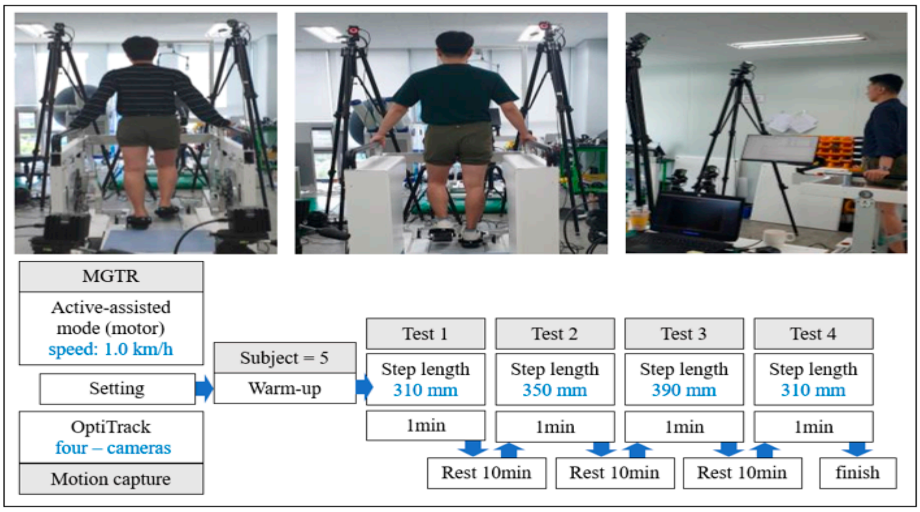

Figure 8. Experiment scene and flow chart.

3. Results

3.1. System Functioning Test

There was no damage as a result of applying a load of 400 kg for 5 min to check the maximum allowable load at the MGTR. The results of the stability test showed that the inclination of the instrument was within 10° forward and backward and 5° in the lateral direction. A load of 50 kg was applied to each of the two-step plates, and no damage occurred even when operating at a speed of 60 times per minute for 100,000 cycles. The noise generated during the operation was measured to be 68.9 dB.

3.2. VR System Test

The error range between the yaw angle measured by the VR device and the angle reference line drawn with the protractor was 99.1%, which was the maximum error rate after measurement. Additionally, the maximum time taken to receive the data from the operating program to the VR program was 14 ms.

3.3. Kinematic Evaluation

Table 1 shows the left and right joint angles and the actual measured step length when walking at 1 km/h, for step lengths of 310, 350, 390, and 430 mm. The ROM values of the hip and knee increased statistically with the step length of the right leg. Three joint extensions and ankle flexions were not affected by the step length. There was no statistical difference in the gait event ratio as the step length increased in both legs.

As shown in Table 2, swing time, stance time, and step duration increased on average. It can be seen that the maximum heel height increases significantly as the step length increases.

Table 1. Results of the joint angle by step length.

		Right Leg				Left Leg			
Set Step Length (mm)		310	350	390	430	310	350	390	430
Hip angle (deg)	Max (flexion)	30.08 ±5.95	32.58 ±3.95	33.73 ±3.05	36.01 ±4.81	27.58 [a,b] ±3.21	29.91 ±2.31	31.94 [b] ±1.25	32.00 [a] ±2.36
	Min (extension)	1.10 ±5.40	0.12 ±1.39	1.07 ±1.83	0.51 ±4.08	0.18 ±3.84	0.10 ±1.22	−0.50 ±1.82	−1.04 ±2.05
	RoM	28.99 [a] ±3.07	32.46 ±3.14	32.66 ±1.94	35.49 [a] ±3.64	27.40 [b,c] ±1.16	29.81 ±2.25	32.44 [c] ±1.90	33.03 [b] ±2.12
Knee angle (deg)	Max (flexion)	44.76 ±7.78	49.02 ±7.10	52.57 ±7.00	56.48 ±5.94	44.01 [a,b] ±1.62	47.14 [c] ±2.81	51.57 [b] ±3.47	54.74 [a,c] ±3.59
	Min (extension)	3.05 ±1.72	3.49 ±1.28	2.57 ±1.96	3.13 ±0.54	1.27 ±0.96	1.44 ±1.86	−0.33 ±3.42	0.86 ±0.68
	RoM	41.71 [a] ±6.62	45.53 ±6.96	50.01 ±5.74	53.35 [a] ±5.83	42.73 [b,c] ±1.19	45.71 [d] ±1.79	51.90 [c] ±6.67	53.88 [b,d] ±3.63
Ankle angle (deg)	Max (dorsi)	29.79 ±5.43	26.87 ±4.77	27.83 ±5.55	32.33 ±4.22	29.04 ±3.02	27.67 ±6.59	28.49 ±7.13	32.16 ±6.95
	Min (plantar)	−5.64 ±3.45	−7.92 ±4.45	−8.85 ±6.96	−7.25 ±5.63	−4.87 ±6.35	−5.32 ±4.77	−5.82 ±6.29	−4.95 ±5.37
	RoM	35.43 ±7.88	34.79 ±6.18	36.68 ±9.39	39.58 ±8.29	33.91 ±5.62	32.99 ±3.66	34.31 ±2.89	37.11 ±2.39
Measured step length (mm)		310.80 ±0.45	352.00 ±1.22	392.80 ±0.45	433.40 ±1.14	311.20 ±0.45	353.60 ±2.19	395.40 ±2.19	435.80 ±1.10

Mean ± SD (standard deviation), [a,b,c,d] $p < 0.05$: Tukey's HSD test, one-way ANOVA at each leg angle variable.

Table 2. Results of the gait event parameter by step length.

	Right Leg				Left Leg			
Set Step Length (mm)	310	350	390	430	310	350	390	430
Swing ratio (%)	68.08	68.00	66.47	70.45	70.17	68.71	67.67	71.46
	±9.09	±8.13	±4.17	±5.04	±7.34	±8.17	±2.72	±4.80
Stance ratio (%)	31.92	31.00	33.53	29.55	29.83	31.29	32.33	28.54
	±9.09	±7.72	±4.17	±5.04	±7.34	±8.17	±2.72	±4.80
Swing time (s)	1.13	1.22	1.26	1.35	1.14	1.20	1.28	1.38
	±0.28	±0.22	±0.21	±0.21	±0.24	±0.06	±0.16	±0.11
Stance time (s)	0.51	0.54	0.63	0.56	0.48	0.56	0.61	0.56
	±0.09	±0.10	±0.03	±0.06	±0.11	±0.17	±0.07	±0.14
Step duration (s)	1.64	1.76	1.89	1.91	1.62	1.76	1.89	1.94
	±0.21	±0.17	±0.21	±0.22	±0.21	±0.17	±0.21	±0.22
Max. Heel height (m)	0.23 [a,b,c]	0.25 [a,d]	0.27 [b,e]	0.29 [c,d,e]	0.23 [f,g,h]	0.26 [f,i]	0.27 [g,j]	0.30 [h,i,j]
	±0.01	±0.01	±0.01	±0.01	±0.01	±0.01	±0.01	±0.01

Mean ± SD (Standard deviation), [a,b,c,d,e,f,g,h,i,j] $p < 0.01$: Tukey's HSD test, One-way ANOVA at each leg gait event parameter.

4. Discussion

This study developed an MGTR that used walking speed to link to a VR system, including a biofeedback system that used step length to control the lower limb joint angle. By adjusting step length according to the speed, it aided in the implementation of a normal gait trajectory for patients with gait problems.

Development and performance tests were performed for each element of the device. The durability was revealed to be four times the maximum allowable load; the contraption also passed the 100,000-cycle load test, with a load applied to each step plate. Noise generated during the operation was measured at 68.9 dB.

Results of the stability and durability tests offered assurance of patient safety while boarding. As the results of the gait trajectory have been verified in previous studies, additional verification was not performed [20].

In the performance test for the VR system, the error rate when matching the gaze and angle was confirmed to be less than 1%. The resolution of the operating system and VR were estimated to be 690 and 118 fps, which guarantees an acceptably immersive experience during the rehabilitation exercise [21].

The angles of the hip and knee joints increased with step length at a speed of 1 km/h; this change was not observed in the ankle joints. This demonstrates that joint angle can be controlled by adjusting the step length. The performance of the joint control equipment of the robot-assisted gait training device for orthopedic exercise was measured. According to the medical device guidance from the Ministry of Food and Drug Safety and Korean standard for medical treadmill (KS P 8405:2007) [22], it should be at least 25 ± 5°, 40 ± 5°, and 20 ± 5° for the hip, knee, and ankle joints, respectively; this experiment showed that the angles for these three joints were at least 27.4°, 41.7°, and 32.9°, respectively. Therefore, the requirements for gait training equipment were satisfied. In general, the average RoM in normal gait is approximately 40°, 60°, and 30° for the hip, knee, and ankle joints [23]. The average RoM of the hip, knee, and ankle joints in Lokomat, a representative exoskeletal MGTR (Hokoma Inc., Zurich, Switzerland), were 45.6°, 60.3°, and 29.2° [24], while those of the MGTR developed in this study were 32.4°, 47.6°, and 36.6°, respectively; however, it was confirmed that the joint flexion and extension conformed to the standards of the training equipment. Because the joint ROM is different depending on the patient's movement function and muscle strength, it is possible to set up a program that sets the step length according to the patient's condition and gradually increases it during training.

In the previous study, the hip and knee joint angles were compared between ground walking and passive (patient active) walking at MGTR [20]. Direct comparison and statistical analysis with this study results are difficult because the conditions of the subjects in this study are different. Therefore, the maximum and minimum angles and range of motion of the knee and hip were compared intuitively (Table 3). As a result, it can be seen that the minimum and maximum joint angle and range of motion measured by the occupant of the motor active MGTR are relatively similar to ground walking than the passive MGTR. This is considered to be the influence of a load and a force generated by the user according to the actuator's walking guidance. Therefore, it is thought that motor active mode will be more advantageous for patients whose purpose is to learn normal gait patterns. The effect in actual patients is planned to be confirmed through clinical studies in the future.

Table 3. Differences of lower limb angle according to gait conditions.

		Min. Angle	Max. Angle	RoM
Hip	Ground walking	−14.56 ± 7.50	54.40 ± 12.59	68.97 ± 14.65
	Passive	24.02 ± 3.16	43.32 ± 5.74	19.31 ± 3.11
	Motor active	0.70 ± 3.31	33.10 ± 4.73	32.40 ± 3.64
Knee	Ground walking	13.85 ± 6.66	93.81 ± 14.31	79.96 ± 19.25
	Passive	60.17 ± 3.41	102.78 ± 6.90	42.61 ± 4.25
	Motor active	3.06 ± 1.40	50.71 ± 7.80	47.65 ± 7.35

In the result of the gait event parameter, the swing and stance phase ratios averaged at 68.8% and 31%, respectively—a ratio of approximately 7 to 3. This is the opposite result from the MGTR, where the ratio of swing and stance during normal walking is 4 to 6. It was confirmed that stance and stance times were twice as large as the swing time. Although the stance time was similar to normal walking, it is necessary to adjust the assist speed in the swing section more quickly because the gait was performed under the condition of 100% robot power assist. When the speed of the swing section increases, the event ratio of the stance is also expected to increase [25]. Alternatively, it is necessary to modify the gait trajectory at the ankle to increase the length of the device driving trajectory in the stance phase from heel strike to toe-off, or to reduce the swing phase from toe-off to heel strike [6,26]. As such, it is necessary to modify the device to implement a gait event similar to a normal gait.

The limitations of this study are as follows. First, in this experiment, the movement of the joints according to the initial step length and speed was confirmed, but additional experiments are needed to automatically adjust the step length according to the walking speed. This function can implement the characteristics of ground walking in which the step length increases when the walking speed increases. Second, the experiment was performed on normal subjects. The final target of user such as stroke and Parkinson's patients were not considered. In addition, the age of the patients was not considered. In general, patients with gait impairment are older. This study was conducted on normal young subjects in a small group. Since the this MGTR is in the preliminary development stage, it is considered that safety problems may occur when a patient with gait movement disorder actually boards. In a future study, we will measure the gait in the advanced MGTR, which is more concerned with safety issues when boarding for stroke and Parkinson's patients. Third, the optical camera system was used instead of the IMU system, which is a simplified gait measurement method used in the patient motion capture device. IMU system can calculate angles, velocity, and angular acceleration of each joint [27]. In a future study, we plan to conduct gait measurement and analysis using IMU system for patients with actual gait impairment. Fourth is that the effectiveness was not confirmed when rehabilitation in this VR-MGTR. It is necessary to conduct an intervention study on actual patients to conduct a comparative study of the training effect between the gait speed biofeedback with VR and MGTR systems, which is the R&D product, and the existing MGTR and VR with MGTR. This will be investigated in future research.

In this system, the VR system was linked with MGTR according to the control of speed and step length when walking, and it is possible to implement it similar to the real world using a simulator. It is possible to develop and apply various programs, as well as a training program for this system, walking on a playground track. The advantages of VR are that it can provide feedback necessary for learning, motivating, and implementing actual body functional states [28]. The robot can be trained repeatedly without space constraints and can provide auxiliary power to perform precise movements similar to those of normal people [29]. This MGTR improves muscle function and brain plasticity by lower-limb motion and muscle contraction with normal gait events. Also, muscle strength can be improved. In gait rehabilitation, the implementation of a normal gait pattern is an important factor. The control of joint flexion and extension, acceleration and deceleration are not normal in patients with brain motor function impairment. It is necessary to learn to induce movement at the appropriate timing according to the gait event factors. It also has the effect of helping the therapist's work. In addition, if the advantages of VR and MGTR are complementarily combined, the effect is judged to be further maximized [30]. It is necessary to apply the diversity of content, such as developing a treatment training program according to the severity of motor function decreased.

5. Conclusions

In this study, we developed a biofeedback system that can implement the actual walking state by synchronizing the system and walking speed of the five-bar linked structure MGTR with the VR system. The development of a more immersive MGTR system that provides feedback on the actual gait state in the VR system by applying the point at which the joint movement varies according to the step length and the characteristics of the gait event and the change in the joint angle of the rider according to the change in various step lengths possibility could be identified. In addition, it was confirmed that correction of the gait event phase was necessary when compared with the general normal gait pattern in the gait analysis results when boarding. It can be seen that it is necessary to provide an immersive feeling more similar to the actual walking by modifying the gait trajectory of the MGTR or by controlling the variable speed using motor control according to the section in one stride. The main contribution of this study is to present the process from developing and manufacturing the mechanical part to deriving the parts that need improvement in the MGTR by measuring and analyzing the actual boarding condition.

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Institutional Review Board Statement: The study was conducted according to the guidelines of the Declaration of Helsinki, and approved by the Institutional Review Board of Wonkwang University Medical Center (WKIRB 2021-02, 10 February 2021).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study. And, written informed consent has been obtained from the patient(s) to publish this paper if applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

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