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Examination of Screen-Indicated Methods of Gait Training System with Real-time Audiovisual Feedback Function of Ground Reaction Force*

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Abstract— **In gait training for walking rehabilitation of patients with stroke hemiplegia or bone joint conditions such as fractures, it is important to recognize the load of the affected lower limbs for improving gait ability and avoiding risks such as re-fractures. A weight scale is used at the actual rehabilitation site to recognize the load. However, in this situation, the trainee must look down to verify whether the scale and their walking posture are correct. In addition, the trainee generally cannot read the load value accurately. Therefore, we have developed a system that can show the load in real time on an eye-level display. By using this system, we expect the patients to be able to perform gait training smoothly while recognizing the state of walking. In this paper, we have reported the results of a clinical trial held at a rehabilitation hospital and an examination of the screen-indicated methods.**

I. Introduction

Rehabilitation training is a field wherein mechatronic and robotic systems can provide effective tools for diagnosis and training. The process depends on algorithms for measurement, control, and analysis that are based on quantitative methodologies and data.

In gait training, several devices have been proposed in the literature previously, and the effects of those used in locomotor therapy have been demonstrated. Egawa et al., together with Hitachi, developed a power-assisted walking support device [1] that trains a subject to walk on independently controllable left and right treadmill belts while holding the body with arm rests and handles. A treadmill is a popular device as it is easy to install and user friendly. However, similar to Lokomat [2], this method has a drawback in that it lacks a sense of dynamic body movement as the acceleration of the body balances out in the direction of movement. Ikeuchi et al. developed a reaction force feedback-type gait training system [3] whose main feature is to provide constant dynamic adjustment of the tension lifting the trainee, based on the information from a ground reaction force.

These devices support the trainee's weight to relieve the loads placed on the trainee's legs. However, the most important point during rehabilitation is to recover good balance and posture during walking. Therefore, we consider that a gait training system must be equipped with a function that can assess the trainee's gait.

In gait training for walking rehabilitation of patients with stroke hemiplegia or bone joint conditions such as fractures, recognition of foot load on the affected side is important to improve gait ability and avoid risks such as re-fractures. Therefore, a weight scale and a mirror are typically used to check the foot load and walking posture at the actual rehabilitation site. However, while using a weight scale, the line of sight during walking is easily directed to the foot, which further worsens the walking posture. In addition, the load can be recognized only from a fixed position. Therefore, the variation of the load during walking increases at the measured position.

Our research goal is to construct a practical feedback system that allows the patient to objectively confirm the walking condition, and to promote motor learning during rehabilitation. Because feedback of the lower-extremity load by visual and auditory information while walking includes elements of simultaneous processing, it is necessary to present foot loads that can be checked easily so that trainees are not confused.

Shimada et al. [4] developed a gait training system with an audio information feedback function to communicate with the trainee on changing the walking load. Ogata et al. [5] developed a ground reaction force information system with a color-depth sensor. Ikeuchi et al. [6] developed a visual feedback function in the gait training system for the patients with leg paralysis. Using this system, the trainees can see their feet via a display without needing to look down, while current and goal footprints are displayed. Meanwhile, our system provides a real-time visual feedback function of the entire body and the load values, and uses a force plate to detect the ground reaction force.

Based on these studies, we have developed a system where the trainee can recognize the load in real time from the eye-level display.[7]

This study reports the outline of our gait training system and the proposed screen-indicated methods. We have also discussed the results of examination of the screen-indicated methods and that of the clinical trial held at a rehabilitation hospital.

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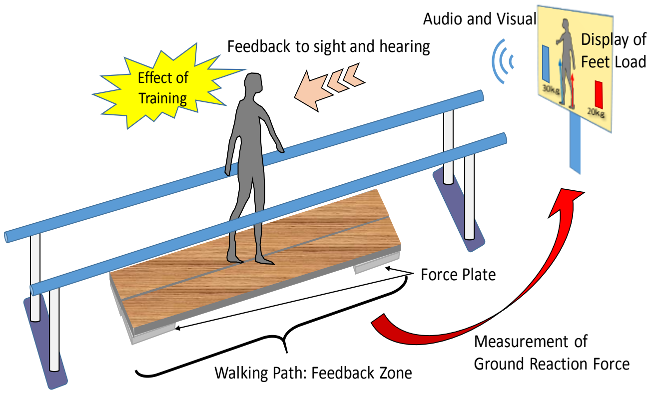
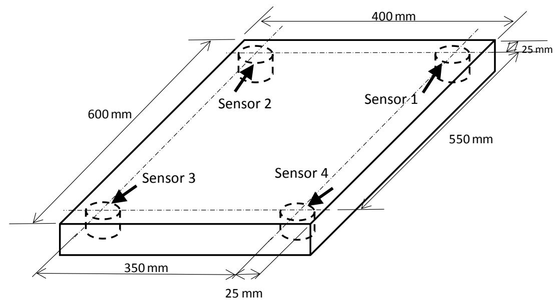
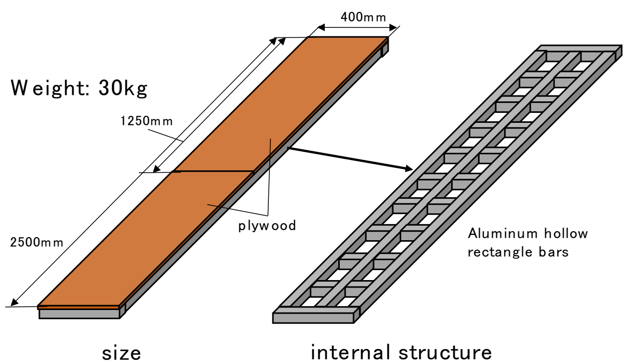


Figure 1. Overview of gait training system.



(a) Force plate.



(b) Walking path plate.

Figure 2. Size and structure of (a) the force plate, and (b) walking path plates.

II. Gait Training System

Figure.1 shows an overview of our gait training system comprising of four force plates (Kistler 9286A), a personal computer (PC; EPSON Endeavor Pro8100), a parallel bar (Takada Bed Inc. TB-1204), AD Interface boards (Interface PEX-321216), a display monitor (Panasonic TH-43EX600), a USB camera (Logicool WebCam C525), and walking path plates. A program to control the system was developed using Microsoft Visual Studio 2015.

The force plates have crystal piezoelectric elements that are used as force sensors and possess good dynamic characteristics. The dimensions of each force plate are 600 mm × 400 mm × 35 mm. Force sensors are installed at all four corners, as shown in Figure.2. Each sensor can measure the three components of the ground reaction force in real time.

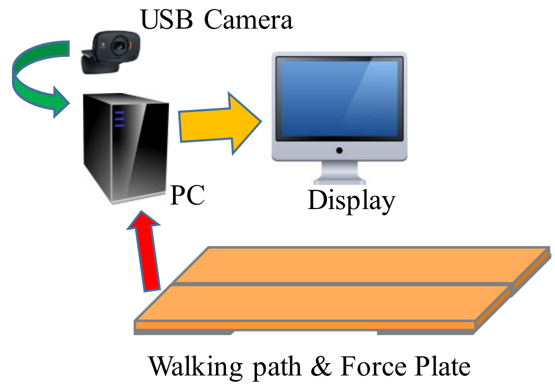


Figure 3. Schematic of the system setup.

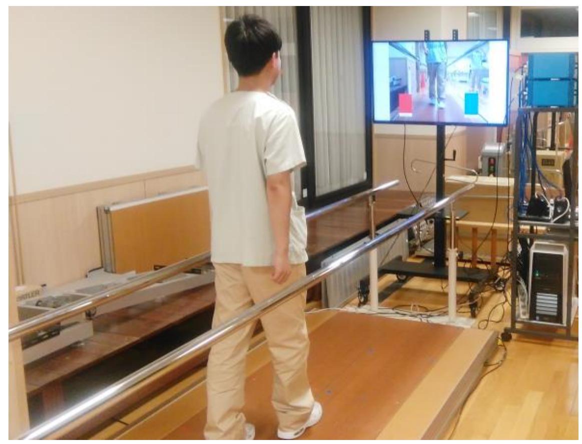


Figure 4. Assessment of the proposed system.

We have constructed the walking path plates using an aluminum frame (Figure.2) to measure the long steps during gait training. These plates were placed directly onto the force plates. The dimensions of each walking path plate were 2500 mm × 400 mm × 62 mm, and an aluminum frame was used for the inner structure. The surfaces of these plates are made of two plywood planks, each with dimensions of 1250 mm × 400 mm × 11.5 mm, to provide a gentle texture for foot contact. The trainee's right and left feet are placed one on each plate. The walking path plate is set on top of the two force plates at either end of the setup. The ground reaction force of the trainee is thus measured using this force plate system.

As shown in Figure.3, The ground reaction force data measured by the force plate is sent to the PC where the three directions of the force components, and the application point of the ground reaction force are calculated. The trainee's walking posture is recorded using the USB camera connected to the PC. The ground reaction force data is transposed into the images and overlaid with the trainee's walking posture, as shown in Figure.1. Thus, trainees can see their posture, and information according to the load on each leg, which is displayed in real time using a bar chart or objects on the PC's display.

Figure.4 illustrates the actual gait training system proposed in this study. There is a waiting area in front of the walking path to measure steady walking data. Also, on the side, an anti-slip surface has been installed to prevent falling.

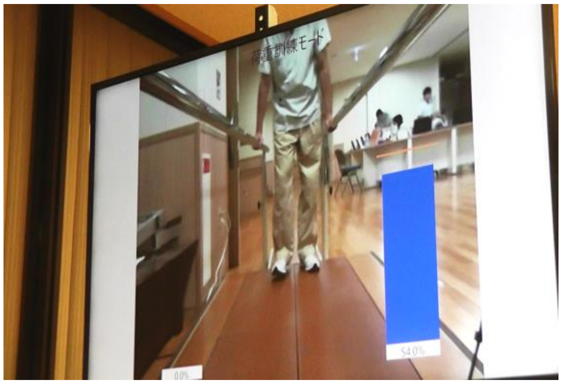
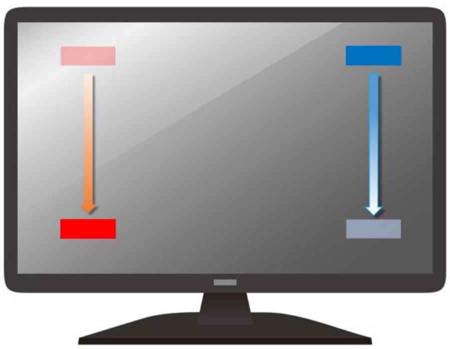


Figure 5. Display showing walking load weight.



(a) Movement of the target.

(b) Display of the experiment.

Figure 6. Display of walking load time (falling target).

III. DISPLAY SHOWING WALKING LOAD WEIGHT

Each patient has different levels of impairment, so they need different rehabilitation training. In addition, it is necessary to display a screen on which the patient can easily check the load, and walk safely. We asked the physical therapists and inpatients at the Beppu Rehabilitation Center for their opinions on the screen display. Based on their suggestions, we have considered a display method that helps the user to check the load weight easily.

Figure.5 shows the "display of the load weight mode." This is used in the early rehabilitation stage when the support ability of the trainee's disabled leg is low. We considered two patient groups specifically. One group consisted of patients with stroke hemiplegia having insufficient support of the lower-extremity and could only walk by supporting the body with their hand, and the other group consisted of patients in the

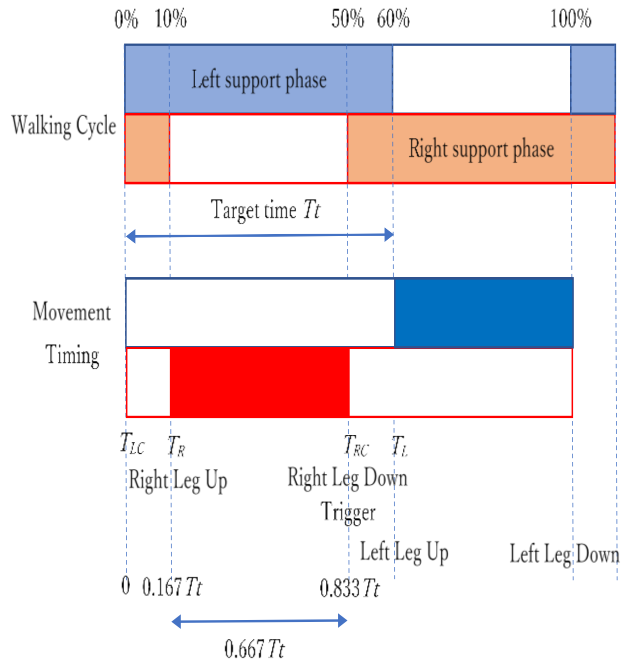


Figure 7. Movement timing of the target.

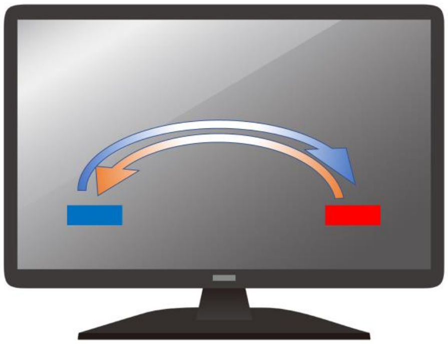
postoperative stage with a painful fractured leg, having difficulty in placing weight on the affected side.

In this condition, the system must inform the trainee of the correct load rate for each leg. In the case of a patient with stroke hemiplegia, the load is different for each leg, and if the load at each leg is greater than the predefined desirable value, the system emits an audible alarm. In addition, this desired value is shown on the display. The trainee can, therefore, try to load the leg as much as possible until the bar chart shows the desired value or the appropriate audible alarm sounds. Thus, the trainee is able to load each leg equally by loading the leg with limited-mobility with a more desirable load (e.g., for a trainee with one fully-mobile leg and the other with limited mobility). Meanwhile, patients who should not be overloaded, that is, those with bone joint conditions such as fractures, are advised to walk in such a way that the bar chart does not exceed the desired value and the alarm does not sound. Thus, the trainee can do effective training safely.

Therefore, when the training for walking is provided using this mode, the load can be applied to the affected foot easily. Later, the support of the hand can be gradually reduced, and the full load can be applied to the affected foot earlier than in the case of conventional method.

IV. DISPLAY SHOWING WALKING LOAD TIME

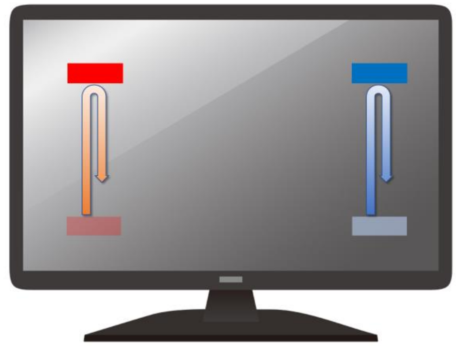
This is used to achieve a symmetrical walking posture during the rehabilitation phase after the affected leg is loaded with full weight. During one walking cycle of a person, it is said that the single leg supporting period is about 40% on each side, and both leg supporting periods are about 20% in total [8]. In general, a typical person with no lower limb disability can walk within this allocated time, however, in the case of a person with lower-extremity disability, who needs rehabilitation, a walking rhythm different from this time allocation is required. Therefore, presenting the target rhythm



(a) Movement of target.

(b) Display of the experiment.

Figure 8. Display of walking load time (arc target).



(a) Movement of target.

(b) Display of the experiment.

Figure 9. Display of walking load time (up-down target).

of walking to the trainee, by showing the signal on the screen display according to this time allocation, it is possible to perform training to reacquire an ideal rhythm by walking accordingly. However, in order to adjust the walking rhythm, it is necessary to introduce something that can be easily controlled by the user. Therefore, we have facilitated three versions of the display of the walking load time that can be selected by the patient.

A. Falling Target Version

This is the first version of the display mode of the walking load time. Figure.6 shows the proposed display layout. Target elements (rectangles) of different colors are displayed on the screen, corresponding to the right and left feet, and the targets move from the top to the bottom according to the desired walking rhythm. The trainee moves the foot in accordance with the targets' movement from the top to the bottom and tries to contact the ground the moment the target falls to the lowest line.

Figure.7 shows the movement timing of the targets. The upper part of Figure.7 represents the time ratio of each foot's phase of one walking cycle. It can be seen that the left foot contacts at the left end of the left support phase. The duration of each single leg support phase is Target time T_t, the target parameter for walking. In the case of the right foot, following contact on the left foot, it is ideal for the right foot toe to be off after $0.167T_t$ (s) and for the right foot to contact after $0.833T_t$ (s).[8] Since the contact time T_{LC} of the left foot can be detected by the increase of the ground reaction force of the left foot, the target for the right foot starts to move at $T_R = T_{LC} + 0.167T_t$ and reach the endpoint at $T_{RC} = T_{LC} + 0.833T_t$. The trainee moves the right foot inward according to it, and the right foot contact time result becomes T_{RC}. An ideal right support phase (lower part in Figure.7, red portion) can then be realized. Similarly, regarding the left foot support phase, visual feedback can be realized by repeating the same process using the right foot contact time T_{RC} as a trigger.

B. Arc Target Version

This is the second version of the display mode of the walking load time. Figure.8 shows the proposed display layout, where the targets move from the opposite side of the moving foot to the moving foot side in an arc. The movement timing is the same as "Falling Target." In this mode, the trainee can walk without losing sight of the target.

C. Up-down Target Version

This is the third version of the display mode of the walking load time. Figure.9 shows the proposed display layout, where the targets start to move from the bottom to the top, and then down to the bottom again. The movement timing is the same as that of the "Falling Target." In this mode, the trainee only needs to synchronize the movement of the foot and the target.

V. CLINICAL TRIAL

We conducted a clinical trial with the subjects (patients) to compare the usage of the conventional mirror and scale with that of using this system. These trial examinations were approved by the Ethics Committee of the Beppu Rehabilitation

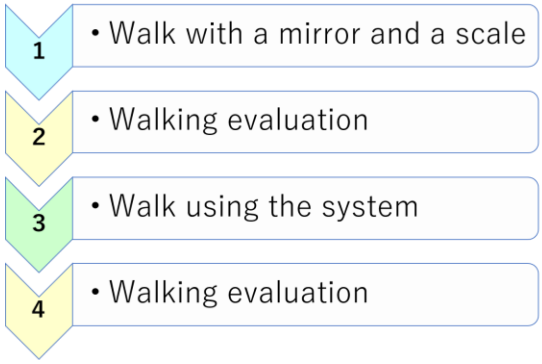


Figure 10. Clinical trial protocol.

Center, and the Research Ethics Review Committee of Oita University Faculty of Science and Engineering.

Hemiplegia subjects were patients with cerebrovascular disease (diagnosed as stage IV or higher in Brunnstrom stage), and stable walking. Subjects with bone joint conditions had load limitation on the affected side due to a fracture of the lower leg and have been advised by a doctor of the possibility walking.

A. *Protocol*

Figure.10 shows the clinical trial protocol as follows:

(1) Regular training of walking using a mirror and a scale was conducted in three consecutive rounds under the guidance of a physical therapist.
(2) Evaluation of walking one round after the mirror and scale was removed.
(3) Regular training of walking using our feedback system was conducted in three consecutive rounds under the guidance of a physical therapist.
(4) Evaluation of walking one round after the system was removed.

B. *Period and number of participants*

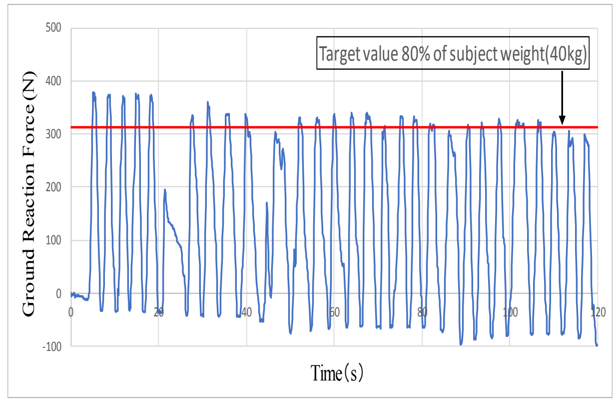
We planned to conduct the trial for nine patients from April 2018 to March 2020 (three patients were trialed at the time of writing this report).

C. *Results*

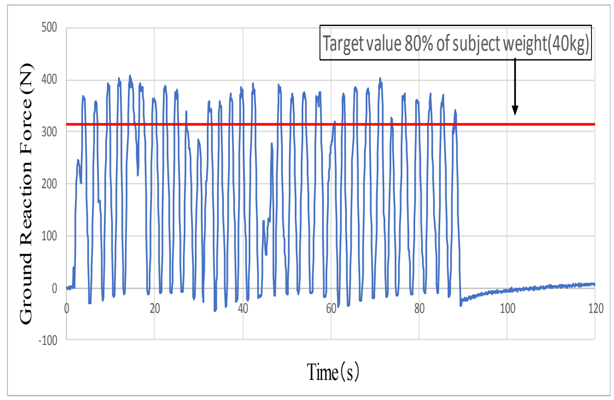
Since the number of clinical trials has not reached the target number at this time, this report describes future possibilities based on a sample of one each in load weight mode and load time mode.

Figure.11 shows the results of a patient with a fractured leg whose one-sided foot load was limited to 80% of the body weight. While using this system (Figure.11 (a)), although a difference of load from the instructed load was found at the start of walking, it was maintained after the mid-period. It is suggested that subject can control his foot load. However, in the case of the conventional method (Figure.11 (b)), a difference of load was found during the whole period of walking. Subject can't be enough to control the foot load. And walk time is smaller than in our this system because subject's one step length is smaller.

Therefore, it is possible for the gait training to be performed for preventing re-fractures using this system for a patient with load limitation such as fracture of the lower-

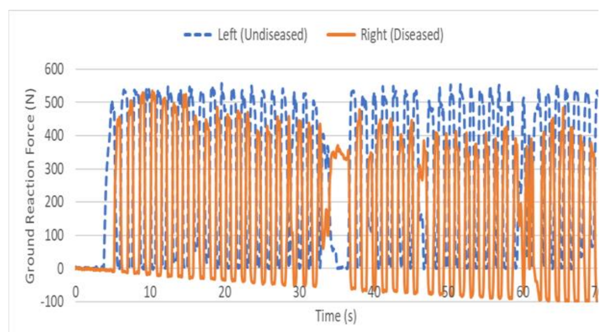


(a) Walk using the system.

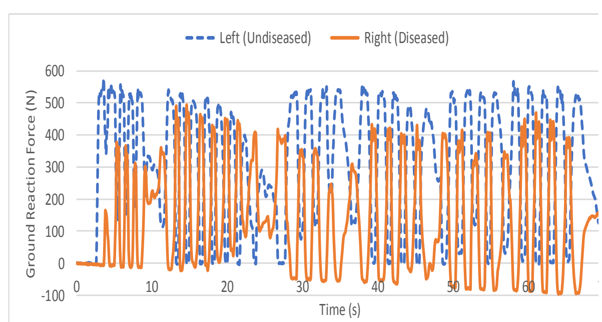


(b) Walk with a mirror and a scale.

Figure 11. Results of clinical trial considering load weight.



(a) Walk using the system.



(b) Walk with a mirror and a scale

Figure 12. Results of clinical trial considering load time (up-down target version).

extremity. In fact, this user was able to walk safely without pain on the affected lower limb.

Figure.12 shows the result of a patient who can walk without using parallel bars that support the upper limbs, and has an asymmetric walking posture due to the difference in the load time for each foot. In the conventional method (Figure.12(b)), the period of right and left foot load disagreed with each other (diseased foot's length was smaller than undiseased). However, while using this system (Figure.12(a)), the period of loading time of the left and right foot were made even. Therefore, the balance function became high and one-sided foot load was less likely to be stressed. In addition, out of the three versions (falling target, arc target, up-down target) of the load time mode, the target patient related with the timing of up-down target version to move his lower limbs. Therefore, the selection of a version is a significant task for the user.

In addition, base lines of the load data in Figures.11 and 12 varied (increased or decreased) with time, and were estimated by the characteristics of the force plates system.

VI. CONCLUSION

We are developing a gait training system with a real-time audiovisual feedback from each foot's load. In this paper, we have proposed screen-indicated methods and have presented the results of the clinical trials that were conducted using the proposed system. The following are the conclusions of our study:

(1) The calculated method of movement timing of the target element on the screen have been proposed.

(2) The procedure of clinical trial has been presented.

(3) The results of the clinical trial are shown. It is suggested that load weight and load time in walking can be corrected to ideal.

In the future, several clinical trial data have to be collected for each of the load weight modes and the three versions (falling target, arc target, up-down target) of the load time mode. Considerable evidence has to be provided from the data to prove the effectiveness of the system. In addition, a new force sensor system will be produced for reducing the cost of our system, eliminate the fluctuation of force base line, etc.

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