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Kinematic analysis of rowing exercise using a motor-assisted rowing machine for rowers with spinal cord injury: a case report

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Objective: We developed a Motor-Assisted Rowing Machine (MARM) for Spinal Cord Injury (SCI), by modification of the Concept II rowing machine, so that the seats could be operated automatically in a backward and forward direction by a motor.
Design: Case report.
Methods: Motor rowing consisted of a chair with inclination control, a motor system, control button, monitor, program, leg supporter, safety belt, and seat. The patients were 2 men rowing athletes with SCI, classified as American Spinal Injury Association class B, participated in the study. Level of thoracic injury ranged from T8 to T10. The subjects rowed at a self-selected stroke rate with 50 watts. Two different rowing methods (static rowing without movementof the seat, dynamic rowing using MARM) were assigned to each participant during 10 minutes; 34 reflective markers were attached to their full bodies. Kinematic data were collected using the Vicon motion analysis system. Based on the full body model provided as a default by the equipment. In the rowing exercise, the rowing motions were divided into Drive Phase and Recovery Phase.
Results: The two rowing methods differ in handle range, seat range, handle and seat ratio, handle velocity, and seat velocity during static and dynamic rowing. The rowing exercise using a rowing machine developed MARM increased tendency to the range of motion in the dynamic method compared to the static method.
Conclusions: The newly developed MARM could be a useful whole body exercise for people with SCI.

Key Words: Ergometer, Motion analysis, Rowing, Spinal cord injury

Introduction

It is reported that compared to healthy adults, people with spinal cord injury (SCI) have a three to five times higher risk of obesity, diabetes, and cardiovascular disorders and their risk of a heart attack increases by approximately 60% [1,2]. Significant changes occur in motor nerves, sensory nerves, and the autonomic nervous system in persons with SCI, and their muscle mass is significantly reduced with limitations of exercise and activity performance [3]. In persons with SCI who use a manual wheelchair, damage to the shoulders occur due to repetitive use, which leads to pain [4]. For this reason, exercises that can restrain them from use of their shoulder protractors and balance of their shoulder muscles are recommended.

Exercise machines for people with paralysis on the lower body due to SCI include an arm ergometer, used with the upper body only, armcycling, used by the lower body only, and a complex exercise method using both, and exercise using functional electrical stimulation (FES) can be used with all types of exercise equipment. FES cycle [5], ERGYS [6], restorative therapies (RT)-300 [7], and FES-rowing [8] have been developed as such exercise equipment. Among them, FES-rowing can induce a significant increase in the level of the hormone leptin, which stimulates decomposition of adipose tissues of patients with SCI and has been reported to be

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useful exercise method from which improvements in aerobic exercise capacity could be expected [8].

For healthy people, there are various forms of exercise machines for strength exercise or cardiopulmonary exercise. In addition, for patients with paralysis due to SCI, various exercise machines are necessary for enhancement of muscular strength or cardiopulmonary functions. If there are many types of exercise machines for patients with SCI and many forms of exercise to choose from, people with various types of disabilities can work out and the frequency of their activities indoors and outdoors can be increased. In this sense, development of exercise machines for patients with SCI can increase their level of health and is essential for increasing their satisfaction and motivation.

For rowing exercises, people with SCI and paralysis of the lower body do not have adequate lower body muscular strength to push the chair they are sitting in. To compensate for this, an electrical muscular contraction method attaching FES to the thigh is used; however, depending on the degree of spinal paralysis, the muscles do not react to FES or there is a limit of exercise time due to rapid muscle fatigue despite application of FES. In addition, without sufficient muscular contraction, rowing exercises have a limitation in appropriate timing for stroke in the drive phase (DP), range of motion (ROM), and performance of exercise intensity [9]. A 3D motion analysis was performed by development of an indoor rowing machine for the disabled using FES and assuming that healthy adults were persons with SCI. However, the motion of each joint could not be identified solely by checking the distance of movement of the markers [10].

In an attempt to correct this problem, this study developed a Motor-Assisted Rowing Machine (MARM; Seedtech Inc., Seoul, Korea) designed to help people with SCI, who were not able to contract the lower body muscles voluntarily, perform rowing exercises by helping the motion of the lower body. This exercise equipment was manufactured by modification of the Standard-type Concept 2 Model-E (Concept 2 Inc., Morrisville, VT, USA) indoor rowing exercise machine, which is often used.

Thus, this study analyzed motions during exercise with an indoor rowing exercise equipment developed for rowers with SCI using 3D motion analysis equipment and attempted a case study to evaluate the usefulness of the equipment.

Methods

Subjects

Subjects of this study were two rowers with SCI. Disabled rowing national team players as rowers, with at least 2 years of experience were selected. Subject 1 (38 year, 90 kg) and 2 (35 year, 80 kg) were classified as class B according to the American Spinal Injury Association (Table 1). The post injury duration of subject1 and subject 2 were 93 and 165 months, respectively. Subject 1 and 2 had a T10 and T8 level of injury respectively. Subjects understood the purpose of the study, and the descriptions of measurements, and provided their informed consent. Subjects were approved by the National Rehabilitation Hospital Ethics Commission (Institutional Review Board-10-B-01).

Methods

A motion analysis of subjects while rowing was performed using the MARM in this study (Figure 1). They were allowed sufficient time before the study to learn how to use the equipment, and an experiment was conducted using two rowing methods in a random order for each subject. The two following rowing methods were used: static rowing, in which the subject performed rowing using only the upper body, while the chair was fixed in a comfortable position,

Table 1. Characteristics of the 2 subjects

Characteristic	Subject 1	Subject 2
Gender	Male	Male
Age (y)	38	35
Height (cm)	180	175
Weight (kg)	90	80
Body mass index	27.8	26.1
Leg length (cm)	97	98
Duration (mo)	93	165
Level	T10	T8
American Spinal Injury Association grade	B	B

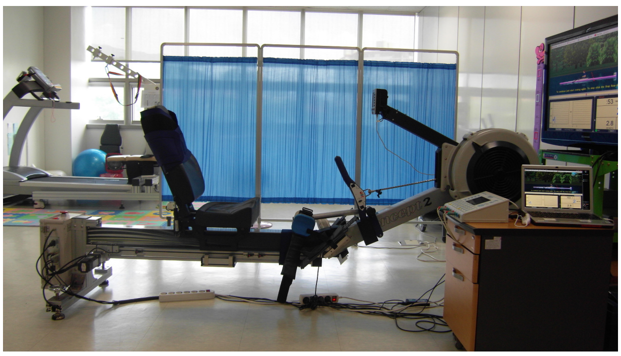

Figure 1. Motor-Assisted Rowing Machine.

and dynamic rowing, which was a rowing exercise with forward and backward motions aided by a motor. A break time of 10 minutes was provided between the rowing methods. In performance of the rowing methods, the subjects controlled the stroke velocity at a comfortable speed, but were asked to maintain 50 watts.

For measurements of data on the rowing motions of the subjects, a 3D motion analysis system with eight infrared cameras (T20, Vicon, LA, USA) was used. Based on the full body model provided as a default by the equipment, a total of 40 markers were attached: four markers on the head, one on the seventh cervical vertebra, one on the clavicle, one on the sternum, two on the following anatomical locations bilaterally: shoulders, lateral elbows, wrists, hands, anterior superior iliac spine, posterior superior iliac spine (PSIS), thighs, lateral knees, tibia, lateral ankles, heels, and toes. However, since the right back and PSIS were covered by the back of the chair of the rowing machine, they were attached to a location proximate to the anatomic position from the other side of the back of the chair, and the belt covered the sternum in order to fix the upper body. For storage and recording of data Nexus ver. 1.7 (Vicon) was used, while the sampling rates were set at 100 Hz. Motions from the data collected were analyzed using Polygon ver. 3.1 (Vicon system). For the rowing exercises, the rowing motions were divided into the DP and recovery phase (RP), and in the static rowing condition, there was only the hand-pull phase, therefore, it was included in the DP. DP refers to the time from the starting posture to the handle brought to the trunk, while RP refers to the time from the end of the DP (finish) to return to the starting position [11].

Data analysis

SPSS Statistics 17.0 (SPSS Inc., Chicago, IL, USA) was used for data processing. The average of the values measured three times for each subject was used. For comparisons of the joint motions of the whole body, a descriptive comparative analysis was performed on the motions of the upper body, mid-portion of the body, lower body, the velocity of each joint, and the ROM. In this study, X-axis direction represented forward and backward from the subject; Y-axis direction indicated upward and downward motions; and Z-axis direction indicated left and right motions. In an analysis of the results, because there was no difference in the Z-axis direction, and therefore, only components in X- and Y-axis directions were compared. In addition, for comparison of the rowing motions of each subject, one stroke was normalized to 100%.

Results

Differences in the Handle and Chair Motions

Results are shown in Table 2. In a comparison of two exercise methods using MARM, the rowing velocity of subject 1 was 25.08 cycle/min in the static method and 17.77 cycle/min in the dynamic method. Subject 2 velocity was 43.31 cycle/min in the static method and 19.17 cycle/min in the dynamic method. The rowing velocity during the static method tended to be faster than the dynamic method. The range of backward and forward motions of the handle in subject 1 showed an increase to 923.67 mm in the dynamic method and from 597.88 mm in the static method. The subject 2 showed also increase to 549.00 mm in the dynamic method from 823.00 mm in the static method.

In the static condition, the ROM while the chair was fixed were 11.00 mm (subject 1) and 5.00 mm (subject 2); however, the range increased to 381.33 mm (subject 1) and 292.77 mm (subject 2) in the dynamic condition. A differ-

Table 2. Movement differences in static and dynamic movement on a motor-assisted rowing machine

Parameter	Subject 1		Subject 2	
	Static	Dynamic	Static	Dynamic
Rowing speed (stroke/min)	25.08 (1.3)	17.77 (0.1)	43.31 (6.3)	19.17 (0.04)
Handle range of motion (mm)	597.88 (46.69)	923.67 (28.02)	549.00 (0.70)	823.00 (5.23)
Seat range of motion (mm)	11.00 (2.00)	381.33 (3.05)	5.00 (0.70)	292.77 (0.21)
Handle and seat range ratio	54.35 (13.63)	2.42 (0.41)	109.80 (25.48)	2.81 (0.29)
Peak handle drive velocity (mm/s)	847.67 (69.63)	947.00 (54.00)	1,175.67 (239.32)	947.00 (212.80)
Peak handle recovery velocity (mm/s)	1,011.33 (203.56)	886.67 (115.24)	1,106.00 (121.34)	996.67 (101.39)
Peak seat drive velocity (mm/s)	48.33 (13.47)	616.00 (11.84)	23.00 (10.94)	616.74 (4.93)
Peak seat recovery velocity (mm/s)	39.87 (8.87)	611.67 (14.52)	26.20 (7.37)	541.67 (2.88)

Values are presented as mean (SD).

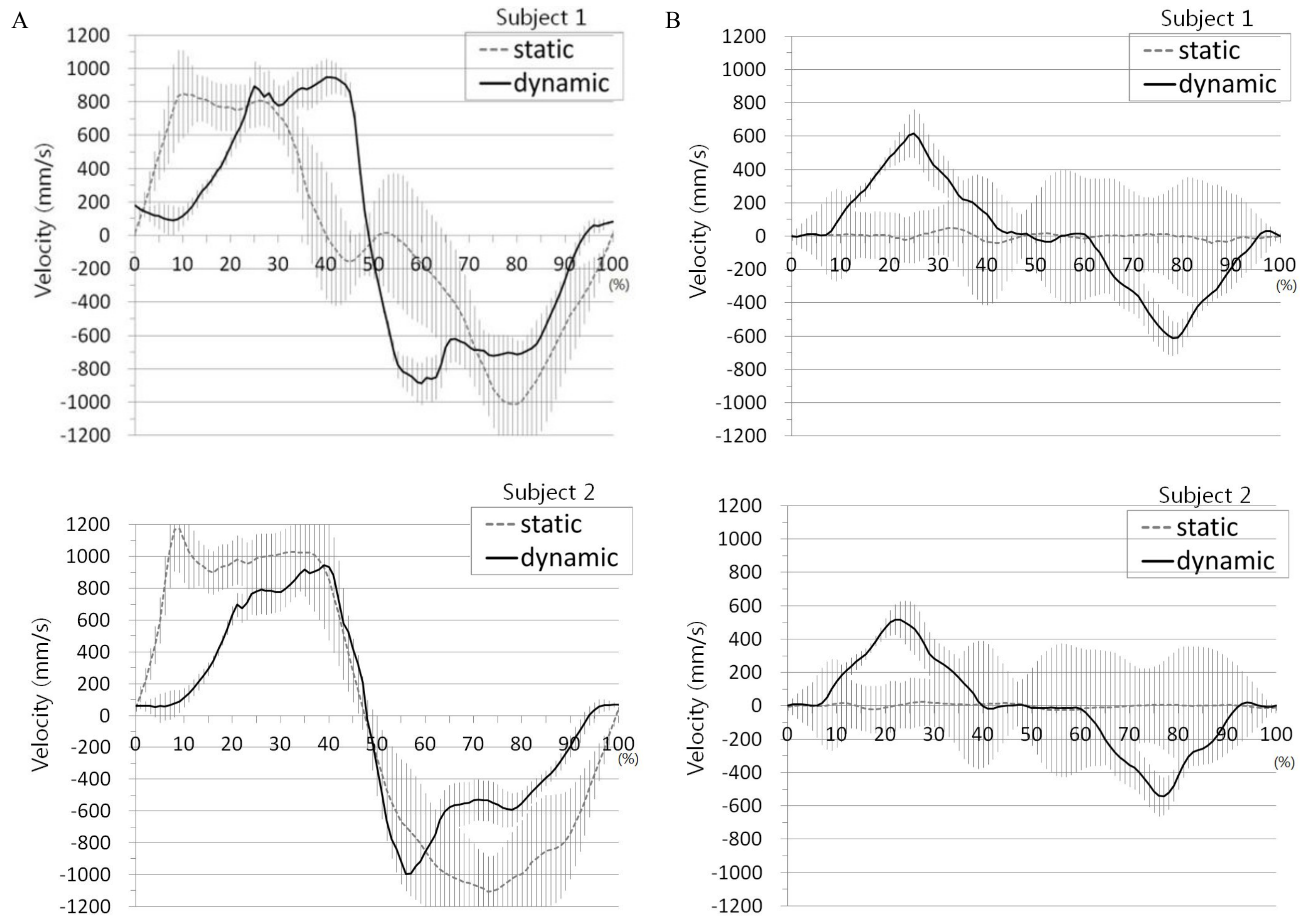

Figure 2. Velocity of the handle (A) and a chair (B) in rowing exercise of subjects.

ence in the ratio of motion was observed between the rowing handle and the chair: 54.35 (subject 1) and 109.80 (subject 2) in the static method and 2.42 (subject 1), 2.81 (subject 2) in the dynamic method. In the DP and RP of the rowing handle, the peak velocity of motion in subject 1 was 847.67 mm/s and 1,011.33 mm/s, respectively, in the static method, while it was 947.00 mm/s and 886.67 mm/s in the dynamic method. The peak velocity of motion for subject 2 in the DP and RP was 1,175.67 mm/s and 1106.00 mm/s, respectively, in the static method, while it was 947.00 mm/s and 996.67 mm/s in the dynamic method. Velocity of the handle and a chair in rowing exercise of subjects is shown in Figure 2.

Upper Body and Lower Body Joint Motions

Regarding the motions of the upper body, in the static method, the shoulder and elbow joint motions appeared over the entire section within the two subjects. In the dynamic method, the shoulder and elbow motions appeared in 25%-70% of sections. Figure 3 shows the motion of the lower body that appeared during the dynamic method, and no motion appeared in subjects in the static method.

Discussion

This case study was conducted in order to examine the effectiveness of a rowing machine developed for people with SCI. The rowing machine was designed for indoor rowing exercise on water, which had been made for training of rowing athletes. However, as its effects on exercise were verified, it is distributed as one of the world's top exercise methods. According to one report, compared to an ergometer in a hybrid form using both upper body and lower body, exercise in the disabled using a rowing machine did not show any difference in the amounts of maximum oxygen consumption and average oxygen consumption and was a more effective exercise machine than a cycling machine [2]. Properly exercising in people with SCI may differ depending on an individuals' exercise capability, which is not much different from the recommendations to exercise for people who are non-SCI [12].

Forms of rowing exercise were divided into drive and recovery phases. The static rowing method is generally used for rowing by people with SCI, while the dynamic rowing method involves a form of rowing using external help using the motions of the upper body and lower body in healthy people. This study compared and analyzed these two exercise forms using the 3D motion analysis equipment.

The rowing method using FES can only be utilized with an existing indoor rowing machine. A brake was used to prevent the chair from being pulled forward as a reaction to the upper body force as in advanced research [11]. In addition, a patient with SCI without any FES cannot use this equipment, despite use of the brake equipment; as a result, there is a limitation in that only certain people can use it.

As for properties of this equipment, the start of exercise and the ROM can be controlled by a switch, and it is supposed to move by the ROM set in advance according to the user's leg length. For a natural rowing exercise, in addition to the motion of the lower body, the upper body has to move back and forth in harmony with the motion of the lower body [13], and the backrest fixed to the upper body with a safety belt should move up and down with the motion of the upper body. In addition, it should include a separate device for a disabled person with SCI without the muscular strength of

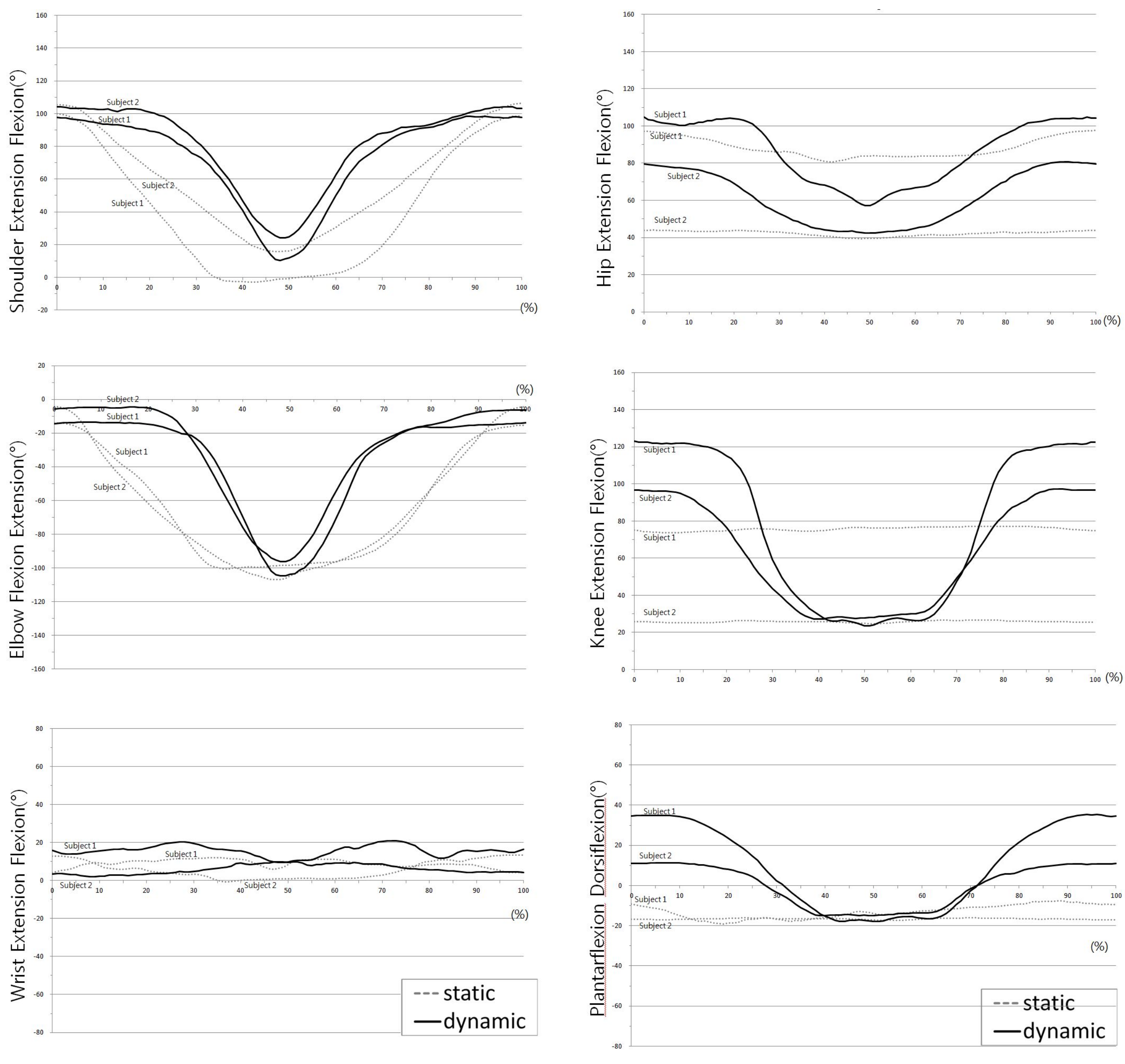

Figure 3. Range of motion in static and dynamic rowing exercise.

the lower body to fix the legs, and he or she should be able to get on the exercise machine, and there should be no inconvenience in operation. The rowing machine developed in this study was devised as an exercise machine so that even a patient with SCI without sufficient muscular strength of the lower body, FES or reaction could use in order to supplement problems associated with existing equipment. In addition, although not used in this study, an FES was connected so that a stimulus signal that could stimulate muscles without any separate manipulation would be delivered to the FES device. This method resolved the issue of the users having to push the button every time, and therefore, enable the users to focus on the exercises.

Halliday *et al*. [9] conducted an analysis of the FES rowing exercise of people with complete damage of the second thoracic vertebra and that of healthy adults as well as the difference in the form of the rowing motion between people with SCI and healthy adults. The average velocity of rowing was 21.5 stroke/min in healthy adults, and 26.3 stroke/min in people with SCI, which was similar to 17.77 (subject 1) and 19.17 (subject 2) in the dynamic method, and higher in the static method than in the dynamic method. The velocity of the chair was 846 mm/s and 608 mm/s, respectively, in DP and RP in normal adults, while it was 616.00 mm/s (subject 1) and 616.74 mm/s (subject 2), 611.67 mm/s (subject 1) and 541.67 mm/s (subject 2) in the dynamic method, which was found to be different from the velocity of motion in normal adults, and it is judged that the velocity of the chair motion was slower in DP than in RP by the stroke motion. This is a matter that requires improvement in this equipment. Compared to healthy adults who naturally show the handle motion by the chair motion, in people with SCI, the ROM of the chair was approximately below 20 cm and the motion initially appeared by FES for 0.5 seconds. In the study reported by Davoodi *et al*. [11,13], the chair motion in normal adults was approximately 479 mm, and the range of 309 mm in this study showed a difference from the result in healthy adults in advanced research. However, the following should be considered: the ROM of the chair, which is dependent on the subject's leg length and the property of the exercise using this machine, should be done within the range so that the knee joints are not completely extended.

In a kinematic analysis of the upper body, in the shoulder joint motion, because rowing exercise should be performed only with the motions of the arms in the static method, stroke motion appeared over the entire range. In the study reported by Halliday *et al*. [9], the elbows curved from 20%-25% of section, and the maximum value of 110^o-130^o was observed in 40% of section. Similarly, in this study, the maximum value of elbow flexion was from 45%-55% of section of subjects. In addition, in a study using a humanoid reported by Hussain *et al*. [14], the ROM of the elbows showed a range of approximately 10^o-125^o. The wrist motion was mostly 0^o-20^o over the entire section, and in a study reported by Halliday *et al*. [9], it showed a distribution of 0^o-20^o over the entire section. In this study, the properties of the shoulder joint motion showed a greater ROM in subject 1 in the static method, which was found in a condition in which the chair was fixed in order to achieve the given target watts, therefore, it is judged that they moved the shoulder joints excessively in order to secure the maximum distance of motion of the arms. The reduction of the shoulder joints could be observed in the dynamic method.

In a kinematic analysis of the lower body, the motion of the hip joints in subject 1 was approximately 20^o in the static method, while in the dynamic method, it was 50^o. Also, subject 2 in the motion of the hip joints was approximately 10^o in the static method, while in the dynamic method, it was 35^o. The ROM of the knee joints in subjects did not show any difference in the static method, while in the dynamic method, it showed a range of 20^o-120^o. In the static method, the position differed depending on each subject because the comfortable position differed for each subject.

In a study reported by Hassain *et al*. [14], the ROM of the knee joints was approximately 20^o-135^o, which was similar to the result of this study, which showed a smaller range than 0^o-140^o in the result of Halliday *et al*. [9] The motion of the ankle joints showed a range of 0^o-40^o, which was similar to that of advanced research.

The limitations of this study are as follows. This was a case study conducted with a small number of subjects. Also, no comparisons were made with the kinematic motions of normal adults with the existing rowing exercises.

Conduct of additional research for analysis of respiratory gas and comparison of the effects of training for a certain period of time will be necessary, and continuous development of various forms of exercise machines to improve the quality of life of people with SCI will also be needed. In addition, increasing the number of subjects in this study should be carried out continuously.

In this case study was investigated 3D exercise patterns of the rowing exercise and analyzed differences of motions by rowing motion. The results are as follows.

First, it was found that performing the rowing exercises using a rowing machine developed in this study increased ROM in the dynamic method compared to the static method in subject 1 and 2. Second, when the motions of each joint in the rowing exercise were compared using a 3D motion analysis equipment, an increase of ROM was observed in the lower body joint in the dynamic method compared to the static method in subject 1 and 2.

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