Upper Extremity Rehabilitation Program Using Inertial Sensors and Virtual Reality for Patients with Upper Extremity Hemiplegia due to Disorders after Stroke

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Abstract. Among the hemiplegic disorders caused by complications of stroke, the functional recovery of upper extremities is slower than the recovery of other functions. In this study, a wireless motion tracking system to transfer motion data on the patient's upper extremity movements was developed using inertial sensors consisting of a three-axis accelerometer, gyro, and geo-magnetic sensor. In addition, motion data were processed and upper extremity movement was represented through a virtual-reality upper extremity rehabilitation program. Quantitative evaluation indicators reflecting upper extremity function could be produced based on performance verification using test subjects with normal upper extremity function. The patients could then assess their own performance status and select appropriate training methods to increase rehabilitation effectiveness without the assistance of a therapist. Future studies will verify the availability and reliability of upper extremity rehabilitation program for patients with hemiplegia, and further develop the three-dimensional upper extremity rehabilitation therapy program.

Keywords: Inertial Sensors, Upper Extremity Rehabilitation, Virtual Reality, Stroke

1 Introduction

Stroke is a cerebrovascular disease resulting from cerebral hemorrhage or cerebral infarction; it is a serious nervous system disease leading to sudden death or physical or mental disorder, and accounts for the third largest cause of mortality in the United States [1]. As its result, even when consciousness is regained after the onset, for an average of 30–40% of patients with hemiplegia, complications such as speech disorder and dementia make it difficult for them to regain a normal life.
Among the various disorders caused by stroke, hemiplegia disorder is one of the most typical, with more than 80% of stroke patients developing a hemiplegic disability [2]. Even though posture and gait rehabilitation are often improved, the restoration of upper extremity function is slower than the recovery of other functions, and if rehabilitation is stopped, the patient will be unable to regain normal function [1]. In most cases, owing to the problem of cost, patients receive rehabilitation training for a period of time and resume rehabilitation exercises at home after discharge from the hospital [3]. When comparing home rehabilitation with rehabilitation in the hospital, there are fewer constraints on time and space in the former, so patients can practice more frequently, for longer periods of time, and according to their own schedule, with the resulting advantage of a better training performance [1]. However, because the patient practices at home without the help of a physical therapist, he/she is unable to assess his/her own state of rehabilitation and determine a treatment program appropriate for the current state of the body.

The currently used upper extremity rehabilitation device is a simple exercise instrument that cannot sustain the interest of patients in rehabilitation over the long term. As a result, the patient spends little time on rehabilitation, and efficiency decreases accordingly. In order to overcome these disadvantages, several studies have focused on rehabilitation using virtual reality technology to provide a variety of training experiences and the ability to assess and track the resulting progress.

Mouawad et al. studied selected tennis and boxing games available for the Nintendo Wii, investigating their impact on balance and upper extremity function in chronic stroke patients, and their possible application in a rehabilitation management program for stroke patients [4]. Although they confirmed an increase in upper extremity function test scores throughout the games, the assessment was conducted using only the existing game system and clinical evaluation by a therapist and a quantitative evaluation of certain extremity movements was not possible.

Zhou et al. conducted a study using inertial sensors attached to the wrist and elbow joints of patients to facilitate real-time observation of the patient’s rehabilitation movements—in the hospital or from home, using a webcam and microphone—by the therapist. After evaluation of the patient’s rehabilitative state, the therapist can recommend an appropriate exercise program [5]. However, this research was intended for assessment of only three kinds of actions–arm stretching, bending, and drinking water–so it would not be suitable as an upper extremity rehabilitation program that requires a wide range of movements. Similarly, Willmann et al. proposed a system to track upper extremity behavior using inertial sensors [1]. In this case, the system itself does not provide a systematic way to exercise, but is dependent on the feedback of the physical therapist.

Therefore, in the present study, a motion tracking system consisting of a typical micro electro mechanical system (MEMS) device using a three-axis accelerometer, gyro, and geomagnetic sensors was developed with an integrated, computer-based system to estimate the position and orientation of the patient's limbs. In the developed system, motion tracking data are transmitted to a PC wirelessly, and upper extremity movement is simultaneously implemented on the plane of the screen using a virtual reality program, allowing patients to assess their status without a therapist’s assistance. The ultimate purpose of this study was to develop a system that allows...
patients to independently select appropriate training methods for upper extremity rehabilitation.

2 Wireless Motion Tracking System

The 15 mm × 23.5 mm inertial sensor (EBIMU-9DOF, E2BOX Inc., Korea) used in the motion-tracking system, consists of a three-axis gyroscope, a three-axis accelerometer, a three-axis geomagnetic sensor, and a 32-bit MCU (STM32F103C8T6). Bluetooth equipment (Parani-ESD110, Sena Technologies Inc., Korea) was used for the wireless communication of experimental data, and the inertial sensors attached to the wrist and elbow joints were wired to the power supply. The system was developed so that inertial sensor data may be transmitted to the host PC at a speed of 100 Hz/s, connecting the inertial sensor and Bluetooth to ensure wireless transmission.

The data are transmitted to a motion tracking algorithm in the upper extremity rehabilitation program for display of upper arm and forearm position and orientation within a three-dimensional (3D) space. The length of the upper arm and forearm of the user is required for precise synchronization of real and virtual movements.

3 Upper Extremity Rehabilitation Program

Various test methods are available for assessment of functions such as mental capacity, motor activity, activities of daily living (ADL) function, and other conditions in order to quantitatively evaluate the overall level of disability caused by stroke [6]. In this paper, the items for evaluation of move and hold functions were derived from a reference test method for evaluating motor function, specifically upper extremity motor function. The move function evaluation item consisted of movements such as flexion, abduction, adduction, elevation, rotation of the shoulder; elbow flexion and extension; and forearm pronation and supination, contained in the representative methods of the Upper Extremity Motion Score [7] and Fugl-Meyer Assessment Scale [8]. The hold functional evaluation item was designed to assess the ability to maintain the arm for a certain period after stretching and lifting the arms to a fixed angle with a reference to the National Institutes of Health (NIH) Stroke Scale [9] and European Stroke Scale [10].

The upper extremity rehabilitation program was developed so that evaluation of move and hold functions includes all motions of the upper extremity motor function in conjunction with a wireless motion tracking system. The host program for representing transmitted data numerically and storing it in real time was designed using Visual C++ 6.0.

The upper extremity rehabilitation program is divided into two segments—evaluation and training, including both the move and hold functions. The program is designed to evaluate upper extremity movement, to confirm the effect of the rehabilitation program using a difficulty-adjustable training program, and to increase
the efficiency of rehabilitation treatment by providing training programs appropriate to the patient's rehabilitation level.

3.1 Evaluation Program

Evaluation of the patient's upper extremity function is divided into the hold function and move function. The evaluation program is started at the lowest level, without regulation of difficulty factors such as target size or movement speed. For evaluation of straight arm raising, the hold function generates a target with the radius of arm length in eight positions, which subsequently increase according to an algorithm of $360/8 = 45^\circ$ as shown in Fig. 1(a) [9,10]. Patients position the cursor (filled circle), representing the trajectory of the hand portion of the upper extremity, to a target (unfilled circle) displayed on a monitor, so that the cursor is maintained in the internal part of the target. Evaluation indicators for the cursor and target area, $T_{in}$ (the time when cursor was kept in the target), $T_{out}$ (the time when the cursor was out of the target), and $D_c$ (the distance between the target center and the center of the cursor, or the distance where the cursor is out of the target), are recorded.

In move 1 function, as shown in the Fig. 1(b), the target moves in a straight line starting from the plane of the shoulder center towards each of the eight positions, which increase at an angle of $45^\circ$ [7,8]. The patient moves the upper extremity along with the target, and $T_{in}$, $T_{out}$, and $D_c$ are recorded. Move function 1 quantifies the functions of the abduction, external rotation, and elevation of the shoulder; elbow flexion and extension; and the forearm pronation and supination, by a linear movement. Move 2 function, as shown in Fig. 1(c), quantifies the functions of abduction, external, and internal rotation of the shoulder; elbow extension; and forearm pronation and supination, using a target that moves along the circumference of a circle in the clockwise and counterclockwise directions.

![Fig. 1. Evaluation Program: (a) hold function, (b) move 1 function, and (c) move 2 function.](image)

3.2 Training Program

In the case of long-term upper extremity rehabilitation, it is necessary to generate interest in training to sustain active patient participation. For example, hold function training, as compared with the move function, requires greater strength and induces boredom more rapidly because the upper extremity must be held at a certain position...
without moving, making it difficult for patients to sustain active participation in training. Thus, the training program developed in this study was designed to combine the hold and move functions so that exercises start only when the cursor enters the target area and is maintained for a period of time.

As shown in Fig 2, the training program is composed of five types of exercises, segmenting the direction of each movement based on the diagnostic assessment of upper extremity movement. As the default setting, 1–5 rounds of exercise consist of a set; however, the program is designed so that the patient may set the repetition times for each exercise. In addition, to improve the efficiency of rehabilitation, the difficulty of each exercise was diversified into five levels by varying the size (the diameter of the circle) and movement speed of the target on which the cursor is located.

The training program moves the target and calculates $T_{in}$, $T_{out}$, and $D_c$ until it reaches the established goal point, difficulty stage, and repetition time for each exercise. To evaluate the training effectiveness after training for a period of time, the $T_{in}$, $T_{out}$, and $D_c$ values of upper extremity movements before and after training are assessed by comparison.

![Fig. 2. Training Program: (a) horizontal movement, (b) vertical movement, (c) diagonal 1 movement, (d) diagonal 2 movement, and (e) circular movement.](image)

### 4 Functional Verification

In order to test the integrated performance of the virtual-reality upper extremity rehabilitation program with motion tracking using inertial sensors, an experiment was conducted with three normal subjects without upper extremity disorders. In the evaluation, evaluation program and four types of training program were repeatedly tested in triplicate. The circular movement (e) was not tested, because it involves the same movement as the evaluation program. For each test, $T_{in}$, $T_{out}$, and $D_c$ were calculated. The lowest difficulty level of the training program was used to make a direct comparison with the evaluation program.

In the results of the mean and standard deviation of $D_c$ in the evaluation program, according to each position of the hold movement experiment, all $D_c$ values were maintained at less than 2 cm. In both the move function (move1, move2) and training movement experiments, all $D_c$ values were maintained at less than 3 cm.

The measurement time in one experiment was 220 s, and so, during the three repeated experiments, $T_{in}$ and $T_{out}$ values for each program were measured for a total of 660 s. For all three subjects, $T_{out}$ measurements revealed it to be less than 1 s. The results of the performance verification with normal subjects confirmed that the upper extremity movements were reproduced in each program’s content based on data from the wireless motion tracking and that cursor evaluation indicators such as $T_{in}$, $T_{out}$, and $D_c$ were measured accurately.
5 Conclusion

In conclusion, it is expected that patients can practice upper extremity rehabilitation independently, without the help of a therapist, using the upper extremity rehabilitation programs developed in this study, and that with subsequent evaluation of upper extremity function and selection of an appropriate training program for upper extremity dysfunction, the effectiveness of rehabilitation would increase.

In future studies, the validity and reliability of the upper extremity rehabilitation program will be assessed for patients with upper extremity hemiplegia caused by stroke. In addition, three-dimensional upper extremity rehabilitation programs will also be developed to ensure more accurate representation of various upper extremity rehabilitation training movements in three dimensions.

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References