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Robotic Stretcher for Spinal Muscular Atrophy Patient: Test of User Controllability with Operating Device and Monitoring System

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Abstract: Diseases such as amyotrophic lateral sclerosis and spinal muscular atrophy (SMA) often cause motor disabilities through the progressive loss of muscle power. Also, many SMA patients must lie horizontally and thus cannot operate a wheelchair. The aim of this study was to develop a robotic stretcher for an SMA patient with severe motor disabilities to enable her to maneuver independently inside a building. The concept underlying the stretcher is that the user should be able to drive the stretcher using a suitable operating device while watching a display feed from cameras mounted on the stretcher. We have developed new devices with an operating device and its algorithm, monitoring system, mechanical frame, and control system tailored to the user's limited abilities (motion in only one finger). We have verified their functions through tests of a prototype machine operated by the target user. The tests were conducted with the machine positioned on the ground to simulate a shopping mall environment. The subject was able to control the machine effectively, aided by the monitoring system that provided visibility of the stretcher's position within the environment. Remarkably, even without specific guidance, the subject could operate the stretcher efficiently. To enhance the stretcher's operability, we considered focusing on controlling the straight motion performance of the mechanical body, which includes two independently motor-driven wheels and casters.

Keywords: Welfare robotics, Service robotics, Medical robotics

Introduction

Diseases such as amyotrophic lateral sclerosis (ALS) and spinal muscular atrophy (SMA) often cause motor disabilities with progressive loss of muscle power. To provide solutions for their mobility needs, we developed a

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robotic stretcher for an SMA patient in a joint project. The user of the stretcher aims to operate it independently, initially inside buildings and eventually outdoors. Conventional electric wheelchairs offer a variety of operating devices. Joysticks and head-joysticks have been developed for smooth wheelchair locomotion (Rofer, 2009), as well as controls that can detect the user's breath. Furthermore, a switch system that controls a self-aided manipulator system has been developed for bed-ridden patients (Hanafusa et al., 2009). However, due to the severe limitation of the current user's motor abilities, it was not feasible to apply any of these devices directly to a stretcher.

With an operating system that senses the bio-signals of the user's body such as by electromyography or electroencephalography, the user can drive the mechanism by activating his/her target muscle (Sankai et al., 2000; Zang & Nakamura, 2006). The combination of electroencephalogram (EEG) and functional electrical stimulation (FES) has been researched for rehabilitation systems (Takahashi et al., 2009). Also, there are some vision-based methods for controlling machines. For example, an upper extremity-supporting robot was developed using a system that could detect gaze motion (Sakaki, 2007, 2009). Visually based assistive robots were developed for holding daily items for bedridden patients. (Kim et al., 2009).

In addition, a multi-sensor system including a camera for monitoring a patient's physiological status was developed (Peng, 2009). However, we could not apply these methods to the target system due to the difficulty of simultaneously both watching environment around the user through a monitor and operating the stretcher by means of the user's bio-signals such as her gaze motion. In addition, the user's field of view is strictly limited by her lying position on the bed. On the other hand, brain-machine interface (BCI) technology has the potential to induce robot motion in association with the user's intentions by connecting the brain directly to the robot (Branner et al., 2004). However, the risk of infection in the user's brain during the surgical operation remains.

Goal of the Robotic Stretcher

The goal of this project was to develop a robotic stretcher for an SMA patient (Fig. 1(a)) to enable her to maneuver independently, first, inside a building and, ultimately, outdoors. Figure 1 (b) shows the concept of the stretcher. The user can drive the stretcher using the operating device despite her disabilities by watching the display feed from the cameras on board the stretcher. Four technical areas needed to be addressed: the operating device and its algorithm, the monitoring system composed with the display and the cameras, and the body frame mechanism supporting the user's body. Also, it was necessary to verify the safety and easy operability of the total system comprising these devices. First, the operating device needed to be operable even with the user's very limited abilities. The subject was able to move her index finger, but in a small range of motion and with little force. Also, the finger could not move in any direction outside the plane of flexion and extension. Therefore, a conventional manual device such as a joystick was not applicable.

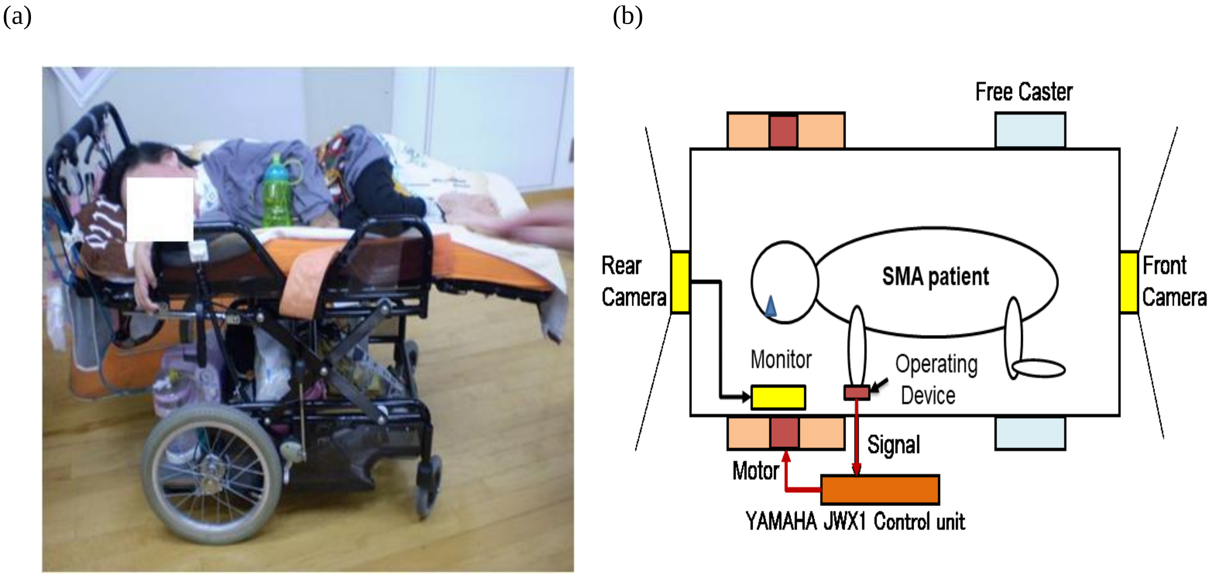

Figure 1. (a) Target user of robotic stretcher lying on the conventional stretcher driven manually by a care-giver, and (b) concept of robotic stretcher for SMA patient for independent operation by the user.

A new device had to be developed to translate a wide range of signals into precise operation, even with the subject's weak finger force and with less freedom of finger motion than in a less-disabled user. Secondly, the monitoring system needs to cover a wide "dead angle" because of the patient's body position; specifically, she was always lying down on the right side of her body in a bed. Therefore, she has a severe restriction to recognize the views toward her head, feet and back. Thirdly, the mechanism supporting the user's body had to be designed to be equipped with the new operating devices, the driving unit, and the monitoring system. Fourthly, some results from our risk assessment of the prototype machine are explained. Also, we show the experimental results for the subject's use of the prototype machine with the new operating device, control system and mechanism.

Operating Device

Motor Ability of Target User's Finger

Because of the paralysis of the user's whole body except for her right index finger, the motor abilities of the finger were researched in relation to the possible operation of the stretcher (Sakaki et al., 2010). The range of motion of the right index finger and the available force exerted by the finger were measured. Figure 2(a) shows the position angles from the most extended to the most flexed. The angle of the finger was defined as the angle between two straight lines from the MP joint to the tip of the finger. The range of motion was 45.0 degrees. The maximum forces in the flexion and extension directions were 4.1*10-4 N and 8.2*10-4 N, respectively. In addition, the maximum frequencies of the flexing and extending motions in the neutral and full ranges of motion were 2.0 Hz and 0.3 Hz, respectively. Based on these results, the motor ability of the target index finger does not seem to be inferior to that of a normal subject in terms of the response and precision of positioning of the finger. However, the range of motion and force of the finger are considerably inferior to those of a normal subject. We considered these conditions in the development of the device.

Switch Circuit for Target User's Finger with Control Hardware

The operating system developed for the prototype model comprises 1) a touch switch circuit and probe, 2) a supporting mechanism to adjust to the shape and posture of the user's finger so it can touch the probe, 3) a controller with microcomputers, 4) a control algorithm installed in the controller to generate the commands to motor drivers from a touch switch circuit, and 5) a display showing the state of the current command.

We have investigated several devices (Kim et al., 2009). However, many sensors present difficulties such as setting the sensor on the user's hand, high costs, and issues with noisy signals and the certainty of executing the STOP command. The subject's finger, being tilted and slightly flexed, cannot evenly touch switches mounted on a flat sheet. Due to her weak finger force, she cannot securely press a switch, resulting in unstable or noisy output signals. Initially, we applied a conductive-type touch switch (Kim et al., 2009; Peng et al., 2009; Sakaki et al., 2011). It could sense a light touch and adapt to the finger's position and shape. However, recent experiments revealed that the user was unable to operate the capacitive touch sensor for unknown reasons, likely due to insufficient change in fingertip capacitance.

Consequently, we replaced it with a mechanical push-button switch. This switch system has been validated through experiments using the switch to control the stretcher motions (Fig. 2(b)). Similarly, the STOP command can be reliably executed by releasing the finger from the probe. The device with the mechanical switch is connected to microcomputers (Arduino Uno) (Fig. 3(a)), producing low-noise output signals. The circuit's output is linked to the Arduino, which calculates the velocity command for the motors to the driver unit JWX-1 (YAMAHA Co.). The command is selected in a round-robin format, changing with each switch activation. The selected command is executed by maintaining contact with the probe for over one second (Fig. 3(b)).

We developed the switch system with the sensor probe and the supporting mechanism. Attaching the operating device to the user's finger took time due to the flexible tube's short length, which hindered switch position adjustment to the index finger. The large sensing base size caused interference with finger operation. Additionally, touching the sensor's back in an extended posture caused user fatigue. Mounting the sensor probe on a long arm's tip facilitated device position adjustment to the index finger. The sensor device, attached directly to the arm, allowed easy finger contact with the probe. We tested the old and new devices, comparing the setting time, command completion time, and command accuracy. The new mechanical switch showed shorter setting and command completion times with the same accuracy level.

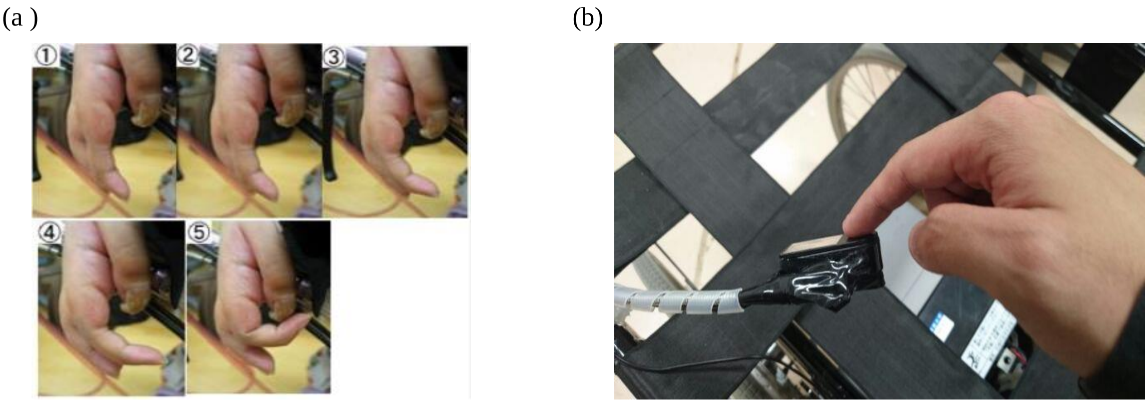

Figure 2. (a) Positions of the target user's index finger. (1) Maximum extension, (2) Light extension, (3) Neutral, (4) Light flexion, (5) Maximum flexion. (b) Mechanical light touch switch suitable for the target use's finger.

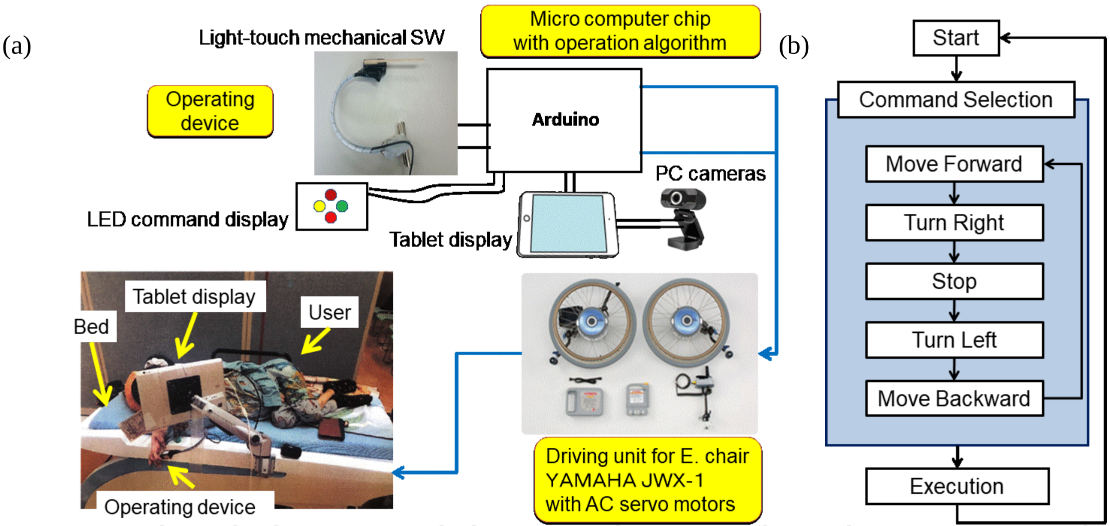

Figure 3. (a) Electric hardware system which comprises the operating device, the microcomputer with operation algorithm and the driving unit YAMAHA JWX-1. (b) The command is selected in a round-robin format.

Monitoring System of Surroundings of Stretcher

The monitoring system surroundings of the stretcher needs to cover a wide "dead angle" because of the patient's body position and posture; specifically, she was always lying down on the right side of her body in a bed (Fig. 4 (a)). The system helps the user to recognize the environment around the stretcher body. The user cannot recognize the surrounding environment on the back, head, and feet. To solve this problem, several web cameras were installed on the stretcher and displayed on the tablet mounted on the stretcher body (Fig. 4 (b)).

As an initial trial, we arranged four cameras around the stretcher to operate using the images. The usability was verified through experiments to determine if the user could recognize the surroundings and operate the stretcher smoothly. The operation experiments with four cameras revealed issues like blind spots and difficulty in distance recognition for walls or other obstacles. Thus, we installed six cameras to six and reconsidered their position and posture. We also added an auxiliary line to the image to indicate distance. However, six or more cameras made the display images small and hard to recognize. We experimentally examined the camera position and posture, obstacle visibility, image delay, continuity, and distance perception (Fig. 4(b)).

We compared the blind spot areas within a 1.5-meter radius half-circle on the screen (Fig. 4(c)). Additionally, we considered risks like obstacle collisions when operating through the camera image and devised countermeasures. Camera position ② had less image overlap than position ①, with a front blind spot width of less than 7 cm. Position ② was installed (Fig. 4(b)). Video continuity was confirmed by checking if the surroundings appeared continuously when a person moved around the device. Distance perception was evaluated by bringing the stretcher closer to the wall, referring to the auxiliary line image, and judging the collision verge distance. We conducted similar experiments with the camera mounting posture tilted downward by 0, 5, 10, and 15 degrees. Image delay did not affect operation, and image continuity was confirmed. However, distance perception remained unchanged with or without the auxiliary line (Fig. 4(d)). Tilting the camera downward improved distance understanding but hindered distant object recognition. Therefore, we decided not to tilt the forward-facing camera.

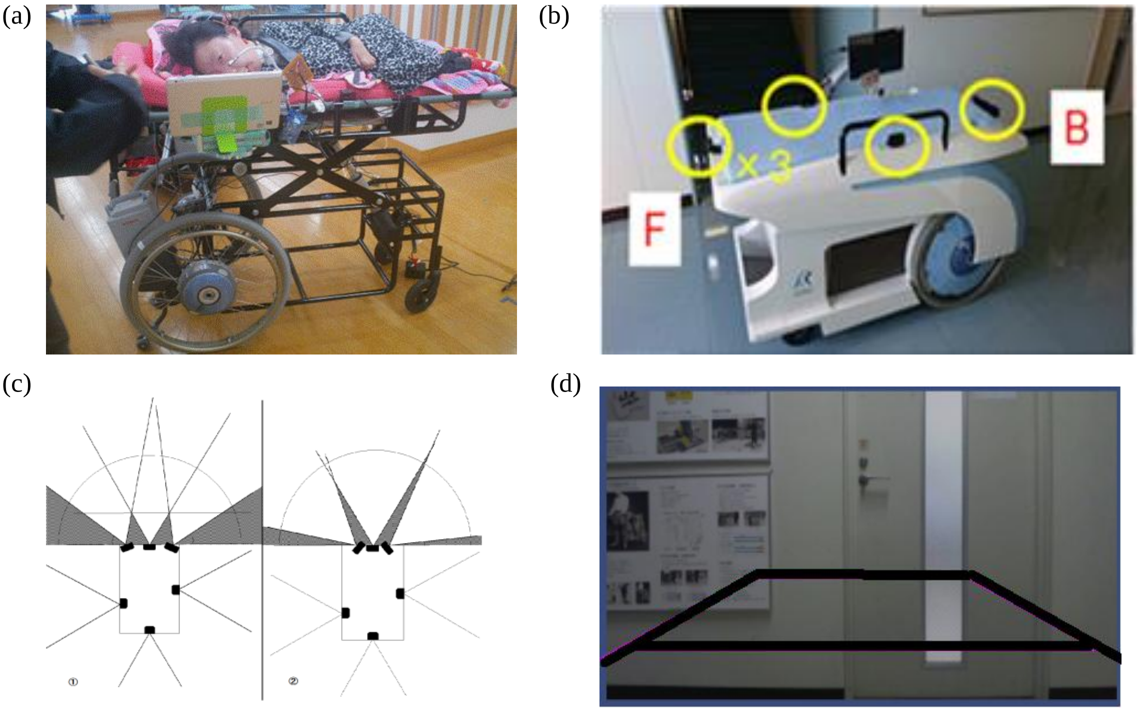

Figure 4. (a) Test scene of the operation by the target user, watching the display. (b) Prototype of stretcher body with exterior and camera positions. F is front side and B is back side. (c) Test results of the area of the blind spots of camera images. (d) The auxiliary line installed in the camera image to get the sense of depth to the wall.

The monitoring system, which utilizes several cameras and displays, will reduce positioning and turning errors by helping the user recognize the environment around the stretcher. To verify the effectiveness of the monitoring system in suppressing errors for straight-line movement, the stretcher was tested to move straight and stop so that the auxiliary line of the side image of the stretcher was aligned with the center of the red mark on the wall in the test room. The stopping errors were measured five times. For turning experiment, the stretcher was rotated 90 degrees to the left while viewing the image in front of the stretcher and stopped so that the image auxiliary line matched the mark in the test room. As a result of the stop accuracy test during a 2-meter straight run, the average error without a camera image was 0.13 m with a standard deviation of 0.04 m. With a camera image, the average error was 0.05 m with a standard deviation of 0.03 m, indicating an improvement in stop accuracy. Additionally, during the stop accuracy test for a 90-degree turn, the average error without a camera image was 10.0 degrees with a standard deviation of 2.2 degrees. With a camera image, the average error was 4.0 degrees with a standard deviation of 0.8 degrees, indicating an improvement in stop accuracy.

Stretcher Body Structure and Risk Assessment

We have developed several stretcher body-frames. The first prototype, made of aluminum alloy pipes (A5052, 3 mm in diameter), was designed to be identical in size to the stretcher the target user currently uses. In designing the frame mechanism, we used the commercial nonlinear finite element analysis, MSC Marc (MSC Software Corporation), to analyze the mechanical performance. Axial force and a bending moment were applied to the frame pipes. The maximum stress inside the frame calculated by FEM (Finite Element Method) was less than the allowable stress for the aluminum alloy, 100 MPa. The results of the stress analysis demonstrated the sufficiency of the frame structure, 600 mm W * 1200 mm L * 700 mm H. The driving unit for an electric chair, namely JWX-1, was mounted on the body frame, including AC servo motors and a motor driver. However, the straightness is still not sufficient. That is, when the machine was moved straight for 5 meters and the deviation to the side was measured 5 times, the deviation to the left was outside the allowable range. It is believed that the battery mounting position is biased to the left and is causing interference with the caster direction. The distortion-free vehicle body described in the experiment results was constructed using steel pipes with a diameter of 3 mm. The dimensions of this vehicle body remain consistent with the previous model, featuring measurements of the same frame structure: 600 mm in width, 1200 mm in length, and 700 mm in height. Notably, the strain issue has been successfully resolved.

We have assessed the risks of the full-size stretcher to improve the vehicle's safety. We have categorized the risks in terms of the risk of operator injury, other risks to the operator's health and the risk to other people or to the operating environment. Based on the results of the preliminary risk assessment, we have improved the intrinsic safety of the stretcher, particularly by adding protective guard rails. In addition, we have developed the camera-based monitoring system so that a user who is lying sideways on the bed can monitor obstacles around the stretcher. According to the standard of risk management (ISO 14121), we have assessed the risks such as the identification of reasonably foreseeable misuse, the hazard identification, the risk evaluation, and the assessment of risk level. Until reaching to the verification of the tolerable situations, the reasonable risk reductions were considered.

Test of Prototype Machine by Target User

The environment for the tests of the stretcher simulated maneuvering around a shop in a shopping mall as shown in Fig. 5(a). First, the stretcher was operated to stop in front of the shop on the reference line, which was the center line of the corridor in the shop. Secondly, the stretcher turned around at 0.5 π to head for the corridor. Thirdly, the machine went straight down the corridor, which was 2 meters wide, for 10 meters into the simulated shop. The margins of the width, which were +/- 700 mm derived from the 600 mm width of the machine at the center of the corridor are the target positioning error at the terminal of the corridor. The performance of the stretcher in positioning on the line, turning around to head for the corridor and moving forward was evaluated.

In the test environment, she was able to operate the device to control the machine stably (Figure 5(b)). The machine moved through the simulated environment in three steps, 1) positioning after maneuvering straight along the wall, 2) taking a stance after turning, and 3) moving forward along the corridor. The trials were repeated five times by the user. The experimental results showed that these three positioning errors were as follows:1) the positioning error in the first step after walking straight was 50 mm +/- 33 mm as an average error with one standard deviation, 2) the turning error translated into the positioning error at the end of the corridor was 680 mm +/- 140 mm, 3) the positioning error at the end point of walking straight was measured in two cases depending on the posture of the casters. In the first case, the position of the casters, which had NOT been adjusted, was aligned with the turning movement. The error was 1260 mm +/- 910 mm. In the second case, the position of the casters was modified so that they were aligned with the forward direction. The error was 705 mm +/- 84 mm. This was the minimum error as the casters are straight forward. The overall operability of the motion in the model environment was evaluated using the Program Evaluation and Review Technique (PERT) [13]. The total positioning error through three motions was 1990 mm +/- 921 mm as the worst case with the maximum error in straight motion. On the other hand, the total positioning error through these three motions was 1435 mm +/- 167 mm as the best case with the minimum error of positioning error in straight motion. These two results are significantly larger than the target range of +/- 700 mm at the end of the corridor. The total error exceeds the target error given the offset and variance of the rotation error. (Fig. 5 (c)).

To suppress these errors, it is necessary to improve not only the operability but also the mobility of the vehicle. The robustness of the straight motion of the stretcher was to be achieved by adjusting the direction of motion. In the worst-case scenario, which produced the maximum errors, the casters were oriented either to the left or to the right with respect to the straight direction of the stretcher. In this situation, the mean of the total operation error deviated from the target (1990 mm) and the standard deviation was also large (921 mm). In the best-case scenario, which produced the smallest errors, the rollers were aligned in the straight direction. Although the mean of the total error differed from the target (1435 mm), the standard deviation was relatively small (700 mm). In this case, that smaller standard deviation means that if we can bring the mean of the actual data closer to the target, the values within that standard deviation are more likely to be within an acceptable range of deviation from the target. If the casters are aligned with the direction of travel, it is easy to achieve the target. However, if the caster orientation deviates from this position, the probability of success decreases. Therefore, we suggest measuring the starting orientation and adjusting the machine's position based on this measurement to achieve the target distance. To achieve this, adjustments should be made to align the rollers in a straight direction. However, after a 90-degree turn, the castors may still be oriented to the left or right. To align the casters with the straight direction, we should consider corrective action after the vehicle has completed the turn to align the casters.

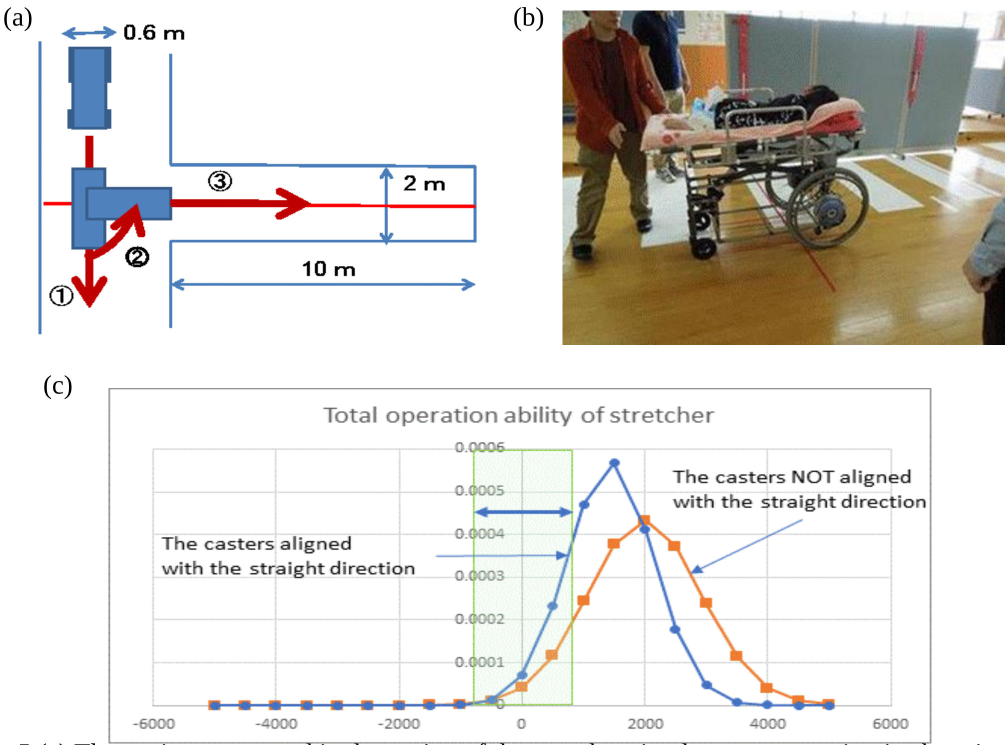

Figure 5.(a) The environment used in the testing of the stretcher simulates maneuvering in shopping mall. (b) Test scene by target user in the test environment. (c) The total positioning error through three motions in the two cases of the casters aligned (bule line) / NOT aligned (red line) with the straight direction in the corridor.

Conclusions and Future Topics

The goal of the project was to develop a robotic stretcher that would allow an SMA user with severe motor disabilities to maneuver independently inside a building. We developed new devices with an operating algorithm suited to the user's limited mobility (single-finger mobility) and verified the functioning of the stretcher through tests with a full-size prototype. In accordance with the mobility of the user's index finger, we developed an algorithm for operating the stretcher. Considering the reliability of the system against operation errors, the intuitiveness of the system, the responsiveness of the machine's motion, and the fatigue of the user, we have applied a conductive-type and mechanical push-button type switches. The mechanical type switches can be applied to the device even given the twisted position and weak force of the target user's finger. The several driving units have been fabricated with a full-size body frame made of aluminum alloy pipes and steel pipes. The target user was given opportunities to control the stretcher using the operating device. We concluded that the user could control the device stably. The controllability of the machine must be improved with more sophisticated interface and control methods that can give more precise directions for the unit to stop along walls and turn corners.

Scientific Ethics Declaration

The authors declare that the scientific ethical and legal responsibility of this article published in EPHELS journal belongs to the authors.

Acknowledgements or Notes

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