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Development of a Walking Support Robot with Velocity-based Mechanical Safety Devices*

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Abstract— **Safety is one of the most important issues in walking support robots. This paper presents a walking support robot equipped with velocity-based mechanical safety devices. The safety devices consist of only mechanical components without actuators, controllers, or batteries. The safety device is attached to each drive-shaft of the robot. If the safety device detects an unexpected angular velocity of the drive-shaft, the safety device can switch off all motors of the robot and lock the drive-shaft. The safety devices can work even if the robot's controller does not work. Firstly, we describe the characteristics of the safety device. Secondly, we explain the walking support robot and the structure and mechanism of the safety device. Thirdly, we show the walking support robot which we developed. Finally, we experimentally verify the effectiveness of the safety device.**

I. Introduction

In Japan, the number of aged people is rapidly increasing [1]. It is expected that elderly patients who need gait rehabilitation will increase. In hospitals, walking support robots are needed that can support the gait rehabilitation of patients in order to decrease caregivers' burdens and to increase patients' independence [2]-[4].

Many researchers have developed various kinds of walking support robots [5]-[7]. These robots can realize many functions for supporting the gait of elderly people by controlling some actuators. However, the robots will move unintentionally and be dangerous robots for users, if their controllers do not work. Therefore, a walking support robot with hardware-based safety devices would be desirable to guarantee safety even if the controller breaks down.

Emergency switches are often used as hardware-based safety devices [8], [9]. When the robot's controller does not work, emergency switches are useful for stopping the robot. However, the patients and/or the caregivers may not be able to push the emergency switch in case of emergency.

In this paper, we present a walking support robot with hardware-based safety devices. The safety devices consist of only mechanical components without actuators, controllers, or batteries. We call the safety device "velocity-based mechanical safety device". The safety device is attached to each drive-shaft of the robot. If the safety device detects an unexpected robot motion on the basis of the drive-shaft's angular velocity, the safety device can switch off all motors of the robot and lock the drive-shaft. The safety devices can work even if the robot's controller does not work.

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This paper is organized as follows. In section II, we describe the characteristics of the safety device. In section III, we explain about the walking support robot equipped with the safety devices, especially about the structure and mechanism of the safety device. In section IV, we show the walking support robot which we developed. In section V, we present experimental results to verify the effectiveness of the safety device. Section VI concludes this paper.

II. Characteristics of Velocity-based Mechanical Safety Device

The characteristics of the mechanical safety device are as follows:

(i) If the angular velocity of a drive-shaft (hereinafter referred to as "shaft") exceeds a preset threshold level, then the safety device for the shaft is activated. We call the preset threshold level "detection velocity level".

(ii) The detection velocity level is adjustable.

(iii) After detecting the unexpected robot motion on the basis of the angular velocity, the safety device switches all motors of the robot off.

(iv) After switching off all motors, the safety device locks the shaft in order to reduce the risk of collision between the robot and humans (e.g. patients or caregivers).

(v) The lock of the shaft is released by rotating the shaft in a direction opposite to the direction in which the safety device locks the shaft.

(vi) The safety device consists of only passive components without actuators, controllers, or batteries.

By the above characteristics (i), (iii) and (iv), we can expect that the safety device prevents high-speed collision between the robot and humans (see Fig. 1). Furthermore, by (ii), we can adjust the detection velocity level according to the requirement of each patient's gait exercise. Additionally, by (v), if a human is pressed against a wall by the robot locked by

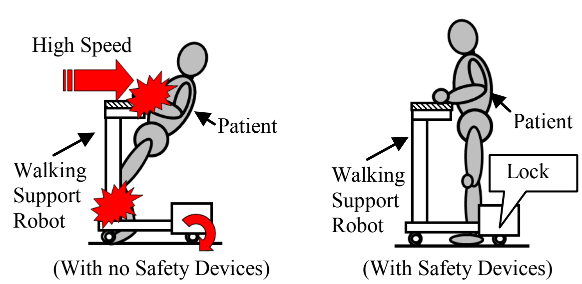

Figure 1. Unexpected High Speed Robot Motion

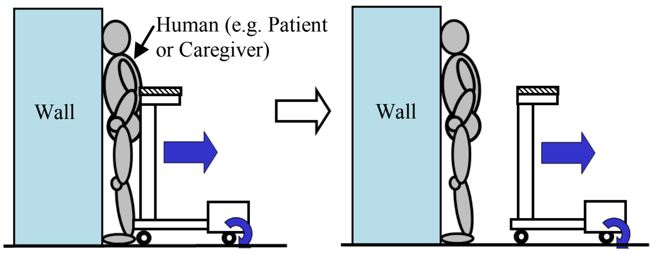

Figure 2. Rescue of a Human Pressed against a Wall by the Robot

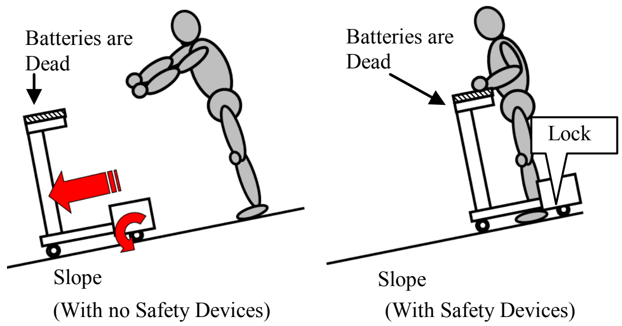

Figure 3. Case Where Robot Batteries are Dead

the safety device, we can easily rescue the human by moving the robot in a direction opposite to the direction in which the human is pressed (see Fig. 2). Finally, by (vi), even if the batteries in the robot are dead, the safety device can act because it requires no power supply (see Fig. 3).

III. Walking Support Robot with Velocity-based Mechanical Safety Devices

Fig.4 shows the walking support robot with velocity-based mechanical safety devices. The walking support robot has two drive units, two casters, and a force sensor. The force sensor is installed between the armrest and the body of the robot. Fig. 5 shows the drive unit. Each drive unit has a motor with an encoder and the motor torque is transmitted to *Wheel* via *Gear 1-A*, *Gear 1-B*, *Shaft A*, *Gear 1-C*, *Gear 1-D*, and *Shaft B*. The robot can move by controlling the two motors on the basis of the force sensor signals and the encoder signals. In order to lock *Shaft A* in clockwise and counterclockwise directions, each drive unit has two velocity-based mechanical safety devices (that is, one safety device for locking in the clockwise direction and another safety device for locking in the counterclockwise direction).

A. Structure of the Velocity-based Mechanical Safety Device

Fig. 6 shows the structure of the safety device. *Gear A*, *Plate B* and *Ratchet Wheel A* are attached to *Shaft A*. *Claw B* is attached to *Plate B* by *Pin D*. *Guide Bar B* attached to *Claw B* is inserted in *Guide Hole B* of *Plate A*. *Shaft A* rotates *Plate A* via the *Torsion Spring*. One end of *Linear Spring A* is connected to *Pin B* attached to *Plate C*, and another end is connected to *Pin A* of *Frame B*. *Plate C* has *inner teeth*. *Guide Bar A* attached to *Claw C* is inserted to *Guide Hole A* of *Plate C*. *Gear B* meshes with *Gear A*. *Rotary Damper* is connected to *Gear B*. *Claw A* is connected to the shaft of *Rotary Damper*.

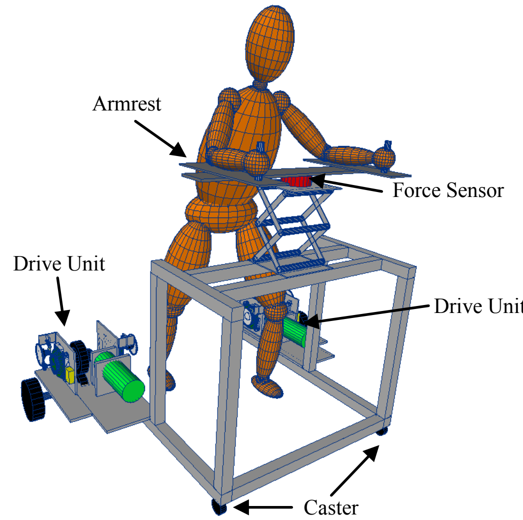

Figure 4. Walking Support Robot Proposed in this Paper

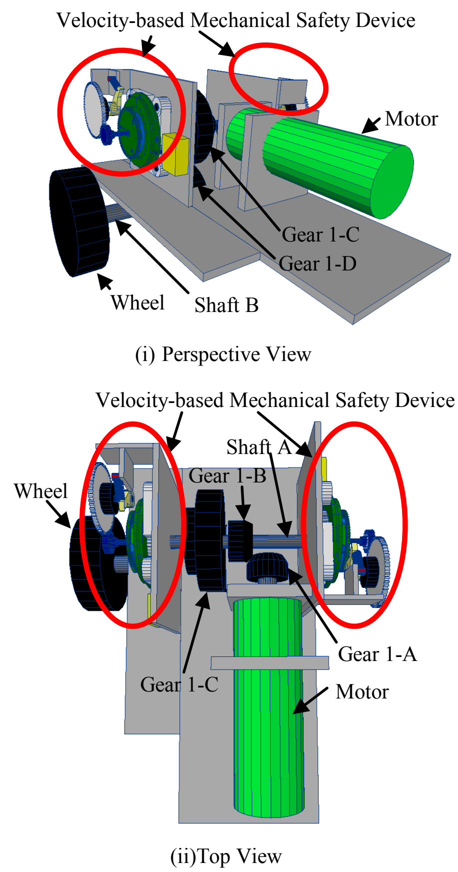

Figure 5. Drive Unit

One end of *Linear Spring B* is connected to *Claw A*, and another end is connected to *Frame A*. *Frame A* is mounted on *Frame B*. *Switch A* which can interrupt electric power supply to all motors of the robot is installed at the position of being pressed by *Pin C* when *Plate C* is rotated. Fig. 7 shows the details of *Plate A*. The ratchet teeth portion is connected to the plate portion via a spring.

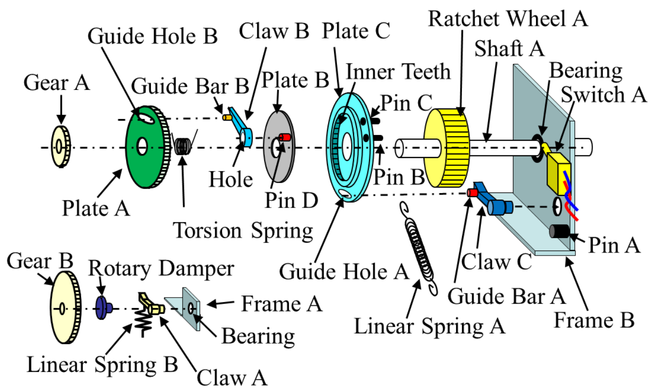

Figure 6. Structure of the Mechanical Safety Device

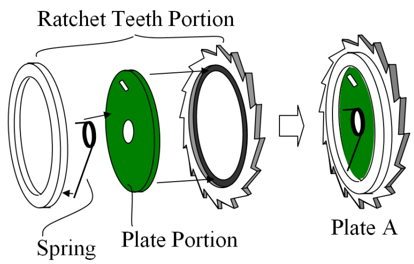

Figure 7. Details of Plate A

B. *Mechanism of the Velocity-based Mechanical Safety Device*

1) *Velocity-based Detection Mechanism*

Fig. 8 shows the mechanism which mechanically detects the unexpected robot motion on the basis of the angular velocity of *Shaft A*. The damping torque by *Rotary Damper* and the spring torque by *Linear Spring B* act on *Claw A*, when *Gear B* is rotated by *Gear A*. As the velocity of *Gear A* (i.e. *Shaft A*) increases, the damping torque increases. *Claw A* rotates by the torque difference between the damping torque and the spring torque, and locks *Plate A*, if the velocity of *Shaft A* exceeds the detection velocity level. The detection velocity level is adjustable by using an adjustment mechanism of detection velocity level, which is shown in *4)*.

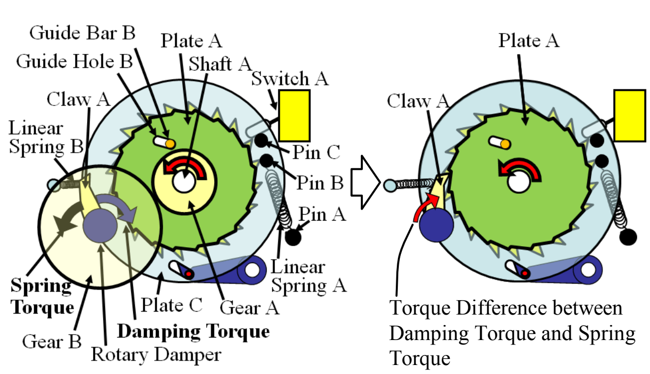

Figure 8. Velocity-based Detection Mechanism

2) *Shaft-lock Mechanism*

Fig. 9 shows the mechanism to mechanically lock *Shaft A*. After *Plate A* is locked, *Claw B* slides along *Guide Hole B* of *Plate A* by the rotation of *Plate B* and contacts with the inner teeth of *Plate C*, as shown in Fig. 9(b). After contacting with the inner teeth, *Claw B* is hooked to the inner teeth and rotates *Plate C* (Fig. 9(c)). By the rotation of *Plate C*, *Pin C* switches off and *Claw C* moves along *Guide Hole A* (Fig. 9(d)). After that, *Claw C* meshes with *Ratchet Wheel A* and thus *Shaft A* is locked.

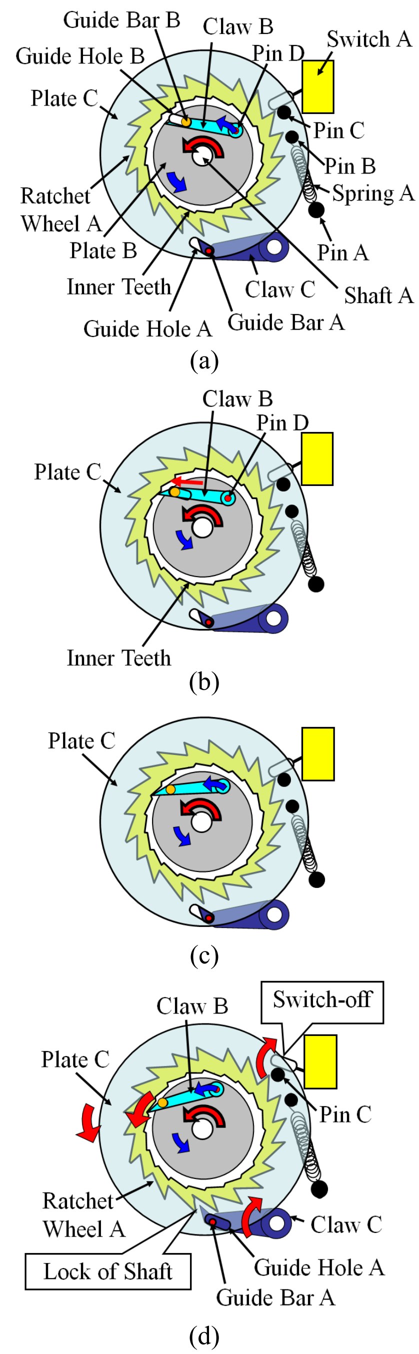

Figure 9. Shaft-lock Mechanism

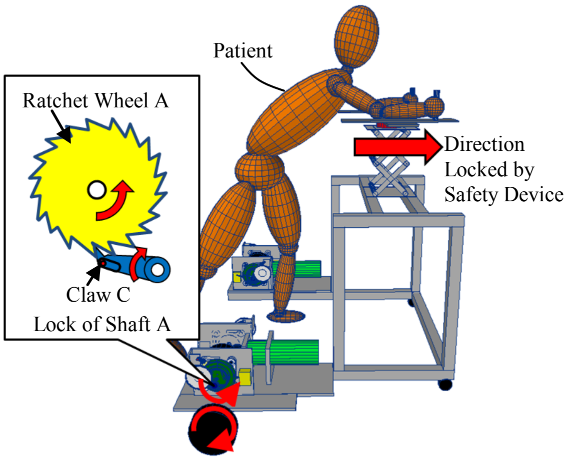

Figure 10. Lock of Shaft A

After *Shaft A* is locked, the damping torque acting on *Claw A* becomes zero. However, if the patient provides a force to the robot in the direction locked by the safety device (see Fig. 10), the lock of *Shaft A* is kept by meshing between *Ratchet Wheel A* and *Claw C*. The lock of *Shaft A* is released by moving the robot to the inverse direction. After the lock of *Shaft A* is released, even if the patient leans on the robot again and the robot moves, the safety device can stop the robot when the robot's velocity exceeds the detection velocity level because the safety device requires no power supply.

3) Mechanism using Multiple Claws B and Multiple Claws C

In the above mechanism, it is preferred that the rotation angle of *Claw B* is as short as possible after *Claw B* contacts with the inner teeth of *Plate C*, because an increase in the angle increases the risk of collision between the robot and humans. Also, in order to be reliably meshed with *Ratchet Wheel A* and *Claw C* even if *Claw B* is hooked to any tooth of the inner teeth, it is necessary that the teeth number of *Ratchet Wheel A* is a multiple of the number of inner teeth of *Plate C* (see Fig. 11). As a method for shortening the rotation angle of *Claw B*, we can propose increasing the number of inner teeth on *Plate C* and the number of teeth on *Ratchet Wheel A*. However, there are limitations on increases in the number of inner teeth on *Plate C* and the number of teeth on *Ratchet Wheel A*, because the safety device installed to the walking support robot is required to be as compact as possible.

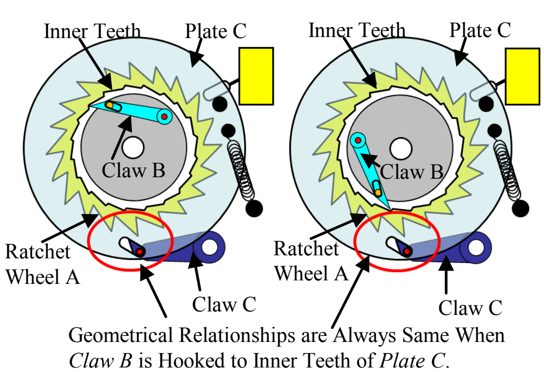

Figure 11. Geometric Relation between Ratchet Wheel A and Claw C

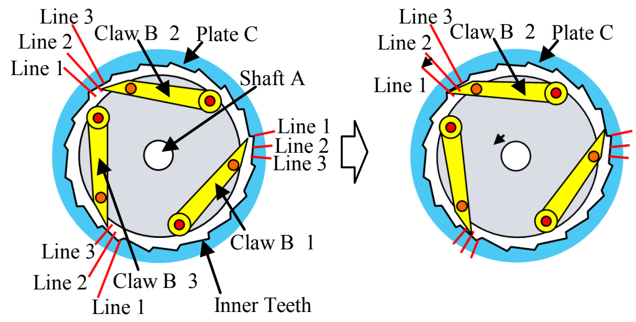

Figure 12. Mechanism using Multiple Claws B

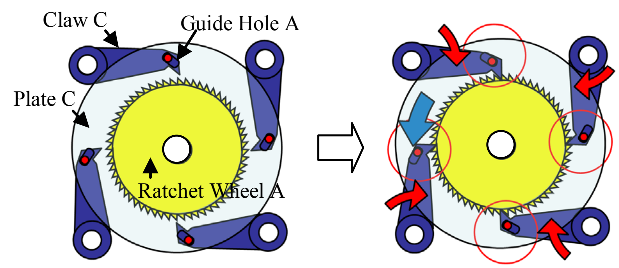

Figure 13. Mechanism using Multiple Claws C

In the following, first, we explain a mechanism using some *Claws B*. By using some *Claws B*, the mechanism provides the same advantage as when the number of inner teeth on *Plate C* is increased. Fig. 12 illustrates the mechanism in which three claws are used. Each claw is positioned as shown in Fig. 12(a). *Lines* 1, 2 and 3 trisect each tooth of the inner teeth. If *Claw B_1* does not mesh with one of the teeth at the moment of contact, only with the movement of *Claw B_2* by one third of the tooth length, *Claw B_2* meshes and rotates *Plate C* (Fig. 12(b)). Note that, in this case, by using *Ratchet Wheel A* having three times as many teeth as the inner teeth, *Claw C* is reliably meshed with the *Ratchet Wheel A*. By using the same technique, if we use *n Claws B*, the mechanism provides the same advantage as when the number of inner teeth on *Plate C* is increased by a factor of *n*.

Next, we explain a mechanism using some *Claws C*. When we increase the teeth number of *Ratchet Wheel A* without changing the diameter of *Ratchet Wheel A*, the strength of each tooth decreases because the teeth are downsized. If the diameter of *Ratchet Wheel A* is increased, the safety device becomes larger. Therefore, as shown in Fig. 13, we propose using some *Claws C*. By the rotation of *Plate C*, the *Claws C* simultaneously move along *Guide Holes A* and simultaneously mesh with *Ratchet Wheel A*. We expect that the force applied to each tooth of *Ratchet Wheel A* will decrease in proportion to the number of *Claws C* because the *Ratchet Wheel A* is simultaneously locked by *Claws C*.

4) Adjustment Mechanism of Detection Velocity Level

Fig. 14 shows the adjustment mechanism of detection velocity level. As shown in Fig. 14, the detection velocity level is adjustable by changing the attachment position of *Linear Spring B* by using two nuts. If the mass and moment of inertia of *Claw A* are so small that we can neglect the inertial torque and the gravitational torque, we can obtain the motion equation of *Claw A* as the following equation:

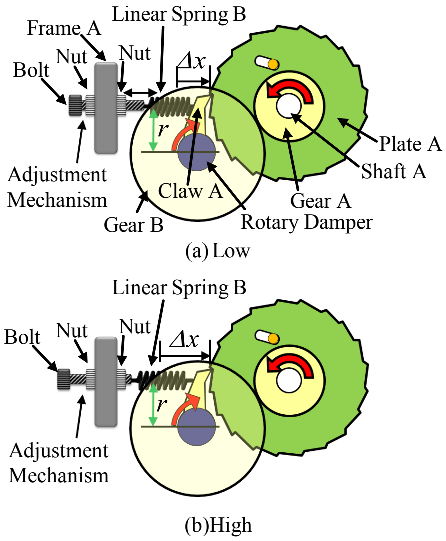

Figure 14. Adjustment Mechanism of Detection Velocity Level

$$c\omega s = kr\Delta x\ , \tag{1}$$

where c is the damping coefficient of *Rotary Damper*, ω is the detection velocity level, s is the gear ratio of *Gear A* to *Gear B*, k is the spring constant of *Linear Spring B*, r is the distance between the shaft axis of *Rotary Damper* and the attachment position of *Linear Spring B*, and Δx is the displacement from the natural length of *Linear Spring B*. From (1), the detection velocity level is represented as

$$\omega = \frac{kr\Delta x}{cs}\ . \tag{2}$$

We can approximately set the detection velocity level by using (2).

IV. Developed Walking Support Robot

We developed the walking support robot equipped with four velocity-based mechanical safety devices. In each safety device, three *Claws B* and four *Claws C* were used.

Fig. 15 shows the developed robot. As shown in Fig. 15, the length and width are 125[cm] and 154[cm], and the armrest is adjustable in height from 85[cm] to 108[cm] according to the height of the patient by using a hand crank.

V. Experiment and Discussion

We experimentally examined whether the developed safety device can achieve the function. Fig. 16 shows the experimental setup. We set the walking support robot on the two rollers and the two spacers, as shown in Fig. 16. Further, we attached some markers on *Gear A* (i.e. *Shaft A*) and *Claw A* of the safety device 1, then measured the velocity of *Shaft A* and the motion of *Claw A* by using a motion capture system (HAS-500, DITECT Corporation) while increasing the velocity of *Shaft A* by the motor. The sampling frequency of the motion capture system was 200[Hz]. We experimented using detection velocity levels of 1.11, 1.70, and 2.14 [rad/s], which were set by using (2). The number of trials was 5 for each detection velocity level.

Figs. 17, 18, and 19 show the typical examples of the experimental results for the detection velocity levels of 1.11, 1.70, and 2.14 [rad/s]. In each figure, the time when *Claw A* locked *Plate A* is indicated by an arrow. Fig. 17 indicates that the velocity of *Shaft A* was approximately the detection velocity level at the time when *Claw A* locked *Plate A*. Furthermore, Fig. 17 indicates that the velocity of *Shaft A* ultimately became zero. Figs. 18 and 19 also indicate the similar results to Fig. 17. Table I shows the average value and standard deviation of the *Shaft A*'s velocities which were measured at the time when *Claw A* locked *Plate A*, for each detection velocity level.

From Figs. 17-19 and Table I, we consider that *Claw A* locked *Plate C* at the time when the *Shaft A*'s velocity approximately became the detection velocity level. Additionally, we consider that the safety device locked *Shaft A* after that, because the *Shaft A*'s velocities ultimately became zero in all the experimental results. Therefore, we can conclude the safety device achieved the function.

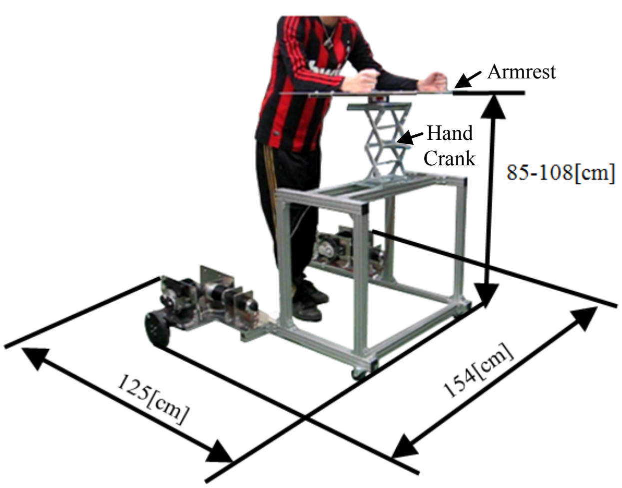

Figure 15. Developed Walking Support Robot

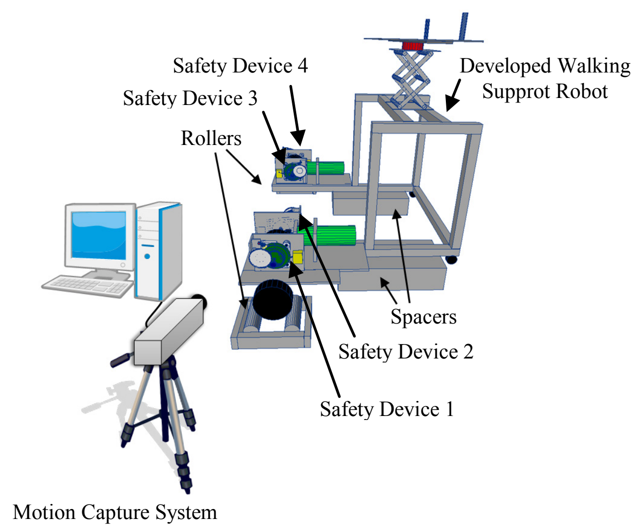

Figure 16. Experimental Setup

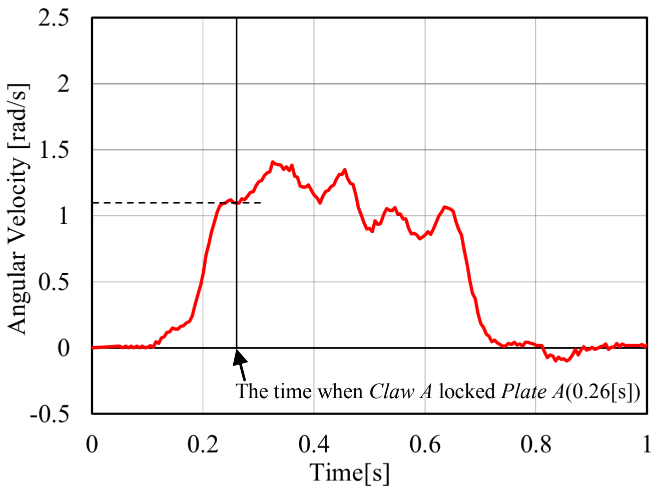

Figure 17. Experimental Result for Detection Velocity Level of 1.11[rad/s]

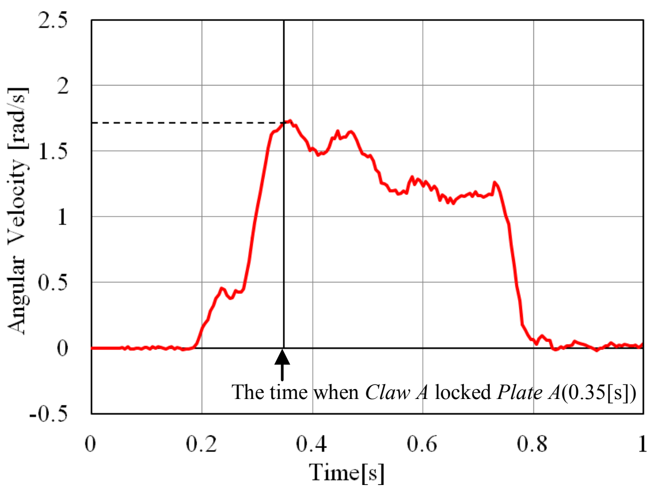

Figure 18. Experimental Result for Detection Velocity Level of 1.70[rad/s]

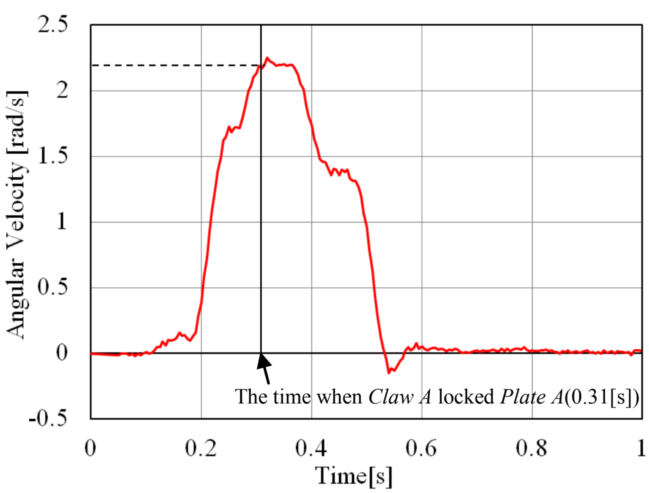

Figure 19. Experimental Result for Detection Velocity Level of 2.14[rad/s]

TABLE I. EXPERIMENTAL RESULTS (DETECTION VELOCITY)

Detection Velocity Level*[rad/s] *(Setting Velocity)	***Average*[rad/s]**	***Standard Deviation* [rad/s]**
1.11	1.04	0.04
1.70	1.72	0.06
2.14	2.22	0.12

VI. CONCLUSION

In this paper, we presented a walking support robot equipped with velocity-based mechanical safety devices. We described the characteristics of the safety device. Additionally, we explained the walking support robot and the structure and mechanism of the safety device. Furthermore, we showed the walking support robot which we developed. Finally, we verified the effectiveness of the safety device by experiments.

In the future, we will examine the usefulness of the safety device in more detail.

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REFERENCES

[1] Cabinet Office, Government of Japan, “Annual Report on the Aging Society: 2010 (Summary),” Cabinet Office Japan, 2011, pp.2-5.

[2] T. Tani, A. Koseki, A. Sakai, S. Hattori, “System Design and Field-testing of the Walking Training System,” in *Proc. of the 1996 IEEE/RSJ International Conference on Intelligent Robots and Systems*, Vol.1, pp.340-345, 1996.

[3] T. Tanioka, Y. Kai, T. Matsuda, Y. Inoue, K. Sugawara, Y. Takasaka, A. Tsubahara, Y. Matsushita, I. Nagamine, T. Tada and F. Hashimoto, “Real-time Measurement of Frozen Gait in Patient with Parkinsonism Using a Sensor-controlled Walker,” *The Journal of Medical Investigation*, Vol.51, pp.108-116, 2004.

[4] Y. Kai, T. Tanioka, Y. Inoue, T. Matsuda, K. Sugawara, K. Ishida and H. Yamamoto, “Prevention of a Patient’s Falling by Using a Sensor Controlled Ambulation Support Machine : Analysis of Leg Muscle Action Based on the Musculo-skeletal Model,” in *Proc. of the First Asian Conference on Multibody Dynamics*, pp.86-96, 2002.

[5] T. Tani, A. Koseki, A. Sakai, S. Hattori, “Control Methods of Walk Training System,” *JSME Int. J., Series C*, Vol.40, No.2,pp.285-290, 1997.

[6] K. Miyawaki, T. Iwami, G. Obinata, Y. Kondo, K. Kutsuzawa, Y. Ogasawara, and S. Nishimura, “Evaluation of the Gait for Elderly People Using an Assisting Cart (Gait on Flat Surface),” *JSME Int. J. ,Series C*, Vol.43, No.4, pp.966-974, 2000.

[7] J. Lee, C. Lee, “Development of Walking Assistance Robot System and Experiment with the Disabled,” in *Proc. of SICE/ICASE Workshop*, pp.219-224, 2001.

[8] Y. Nemoto, S. Egawa, A. Koseki, S. Hattori, T. Ishii, M. Fujie, “Power assisted Walking Support System for Elderly,” in *Proc. of the 20th Annual Int. Conf. of the IEEE Eng. in Medicine and Biology Soc.* , Vol. 20, No. 5, pp. 2693-2695, 1998.

[9] Y. Kai, T. Tanioka, Y. Inoue, T. Matsuda, K. Sugawara, Y. Takasaka and I. Nagamine, “A Walking Support/Evaluation Machine for Patients with Parkinsonism,” *The Journal of Medical Investigation*, Vol. 51, pp.117-124, 2004.