Analysis of Fall Accident Motion during Walking Using a Lower-Limb Exoskeleton Robot

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***Abstract*—Fall accident often results in a serious damage to physically weak persons such as elderly persons. It is important to understand the mechanisms of human fall accident motion and recovery motion to prevent the fall accident. In order to study those mechanisms, external disturbance force is given to a walking person using a lower-limb exoskeleton robot to generate the falling accident motion on purpose and analyze the recovery motion in this study. By applying the lower-limb exoskeleton robot, any disturbance force can be added at any timing to the person during walking. The results of this study are used to provide the fall prevention algorithm in the lower-limb power-assist exoskeleton robot. Furthermore, the results could be used for physical training for elderly persons to prevent falling accident.**

***Index Terms*— falling accident, fall prevention, trip recovery, walking, lower-limb exoskeleton, robots**

I. Introduction

Each year, many persons suffer a serious injury as a result of fall accident. Sometimes, fall accident leads to death in the worst case. Especially, physically weak persons such as elderly persons tend to be victims of fall accident because their motor, sensory, and balancing abilities are deteriorated and their reaction time becomes slow. Although many power-assist exoskeleton robots have been developed to assist the deteriorated function of the physically weak persons [1]-[8], only a few robots have functions to prevent fall accident since fall prevention is difficult to realize especially for the dynamic motion.

In order to prevent fall accident, it is important to understand the mechanisms of human fall accident motion and recovery motion. Forner *et al.* [9] and Shirota *et al.* [10] performed the experiment in which external disturbance force is given to a walking person by pulling a string which is attached to the shoes or ankle joints to analyze the mechanism of human fall accident motion. Pijnappels *et al.* [11] and Schillings *et al.* [12] carried out the experiments in which an obstacle is given to a walking person to make collision between the obstacle and the person's foot for the same purpose. Furthermore, slippery floor [13] or mobile floor [14]-[16] has been prepared to induce fall accident motion in experiments in some studies. In those studies, human fall accident motion was generated under the limited condition. Tucker *et al.* [17] gave disturbance to the knee joint of walking persons in the experiment to observe their reaction motions.

In this paper, a method in which human fall accident motion and recovery motion are generated with a lower-limb power-assist exoskeleton robot is proposed in order to analyze their mechanisms in experiments. By applying the lower-limb exoskeleton robot, any amount and any direction of external disturbance force can be added at any timing to the walking person. Therefore, unlimited natural condition for the fall accident can be realized in the experiment with the lower-limb exoskeleton robot.

As a first step of the study, experiments in which the forward and backward disturbance force is given to the swing leg of walking persons are carried out. The reaction motion of the persons in the experiments is analyzed in this paper. The analyzed results suggest that the swing leg is used to cancel the angular momentum change and the impedance of the support leg is increased to generate the recovery motion when unexpected disturbance force is given to the swing leg in the backward direction.

Figure 1. Lower-limb exoskeleton robot.

II. Lower-Limb Exoskeleton Robot

In order to give external disturbance force to a walking person in the experiments, a lower-limb exoskeleton (Fig. 1) which assists hip, knee, and ankle joints of the user is used in this study. Here, the robot is considered as a device to generate certain external force at the user's foot. The robot consists of links, DC motors (RE40, Maxon),

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encoders (MR Type L, Maxon), force sensors (USL06-H12-500N-AP, Tec Gihan Co.), tactile switches (B3F-1020, Omron), and holders (waist, thigh, shin, and foot). Three-DOF motion (hip flexion/extension, knee flexion/extension, and ankle dorsiflexion/plantarflexion motion) of the user can be assisted by the DC motors of the robot. Each joint angle is measured by the encoder. The force sensor is attached between the link and the holder, so that the generated force caused by the motion difference between the user and the robot can be measured.

In this study, force control is applied in the robot to control the interaction force with the user. The relationship between the generating force at the tip of the user's foot and the robot joint torque is given as:

$$\tau = J^T F \quad (1)$$

where $\boldsymbol{\tau}$ is the robot joint torque vector, $\boldsymbol{F}$ is the generating force vector at the tip of the user's foot, and $\boldsymbol{J}$ is the Jacobian matrix.

Force control law to control the generating force at the tip of the user's foot is shown as:

$$\tau_f = J^T\{K(F_d - F_m) + F_d\} \quad (2)$$

where $\boldsymbol{\tau_f}$ is the robot joint torque command vector, $\boldsymbol{F_d}$ is the desired generating force vector, $\boldsymbol{F_m}$ is the measured generating force vector, and K is the force feedback gain.

III. Experiment for Falling During Walking

In order to analyze human fall accident motion and recovery motion, experiments are carried out to generate those motions with a lower-limb power-assist exoskeleton robot on a treadmill (TOEILIGHT 870). The walking velocity of the treadmill is defined as 2.0km/h. Lanyard is attached to the robot from the roof top of the treadmill for the safety reason. Therefore, the subjects do not fall down on the ground even if they lose the balance.

In order to observe the muscle activities during the recovery motion, skin surface electromyographic (EMG) signals of major lower-limb muscles of the subjects (i.e., tensor fasciae latae, rectus femoris, vastus medialis, vastus lateralis, semitendinosus, biceps femoris, gastrocnemius, and tibialis anterior) are measured with 2kHz sampling frequency in the experiment. The location of each electrode for the EMG signal is shown in Fig. 2. Root mean square (RMS) of the EMG signals is calculated to extract the feature using the equation written below:

$$\mathrm{RMS} = \sqrt{\frac{1}{N}\sum_{i=0}^{i=N} v_i^2} \quad (3)$$

where v_i is the voltage of the measured EMG at ith sampling and N is the number of segments (N = 200). Two young healthy male subjects participated in the experiment.

Motion capture systems (V120 Duo, OptiTrack) are used to monitor the subject motion from the right and the left sides of the subject. Fig. 3 shows the location of markers for the motion capture systems.

In this study, two kinds of experiments are carried out. The first experiment is performed with and without wearing the exoskeleton robot to figure out the effect of wearing exoskeleton robot for the subject's walking motion. In the case of the experiment with wearing the exoskeleton robot, the external disturbance force is not given to the subjects. That means the desired generating force is defined as zero, so that the robot just follows the subject motion without disturbance. Therefore, the robot is controlled not to disturb the user's walking motion in the experiments.

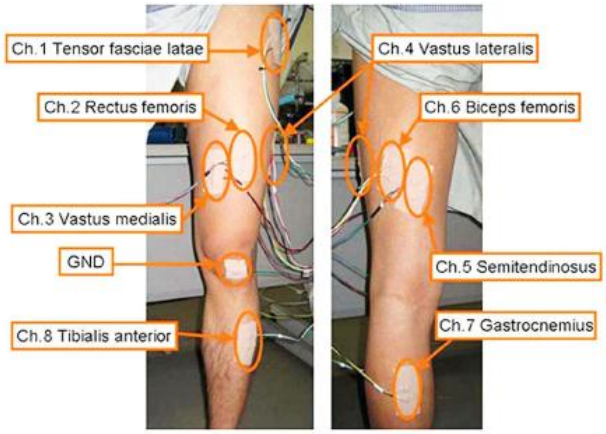


Figure 2. Location of each electrode to measure EMG.

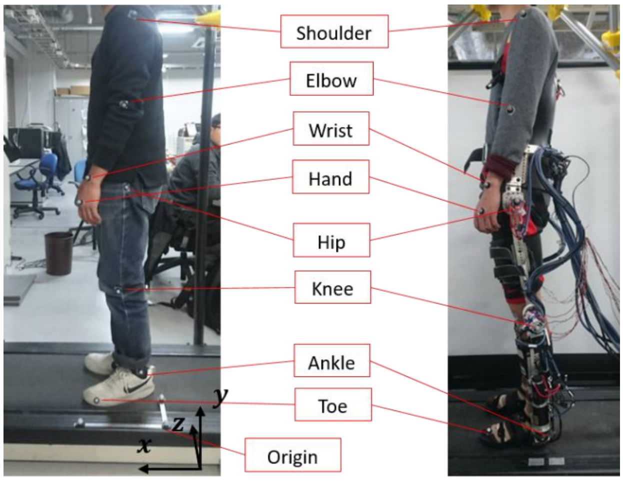


Figure 3. Location of each marker to measure motion.

The second experiment is performed to generate the fall accident motion and recovery motion by generating the external disturbance force with the exoskeleton robot. In this experiment, arbitrary external disturbance force is given to the tip of the foot of the swing leg of the subject at the arbitrary timing randomly during walking. The direction, amount, timing, and duration of the external disturbance force is randomly changed. The parameters of the external disturbance force changed in the experiment is shown in Table I. Giving the external disturbance force to the backward direction is similar to the stumbling situation.

TABLE I. PARAMETERS OF DISTURBANCE FORCE IN EXPERIMENT

Direction	Forward Backward	
Amount	Forward: 0-20 N Backward: 0-40 N	Amount of Change: 1 N
Timing	0-80 % in Swing Leg	Amount of Change: 1 %
Duration	100-700 ms	Amount of Change: 10 ms
Applied Point	Tip of left foot during swing	

IV. ANALYSIS OF EXPERIMENTAL RESULTS

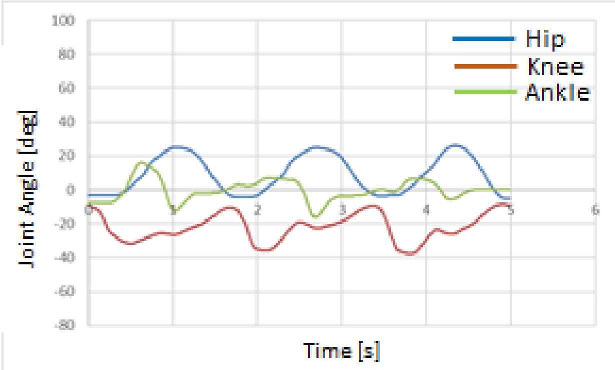
A. Experiment 1

The results with and without wearing the exoskeleton robot in the first experiment are shown in Figs. 4 and 5, respectively. Figs. 4(a) and 5(a) show that the walking motion with and without wearing the exoskeleton robot is not completely the same. The time ratios of the swing leg and the support legs during walking with the exoskeleton robot with respect to those without the exoskeleton robot are 1.11 and 0.992 with the subject A and 1.07 and 0.963 with the subject B, respectively. In both subjects, knee flexion angle and ankle plantar flexion angle are reduced and hip flexion angle is slightly increased in the swing leg with the robot, although the foot-floor clearance is almost the same. One of the reasons of these motion difference is the constraint of the sole part of the exoskeleton robot. Motion disturbance caused by force control error may be another reason of the motion difference.

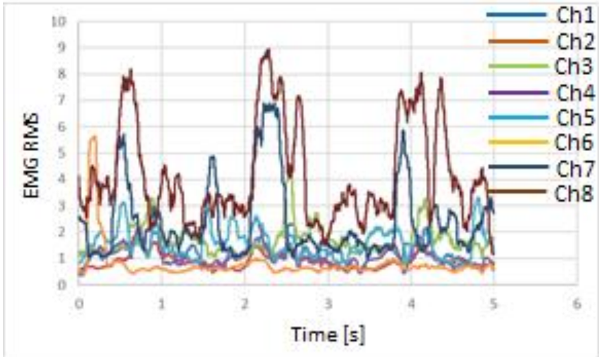
Regarding the EMG signals, the amount of the signals of ch.3-8 are increased to make up for the decrease of the ankle plantar flexion angle results from the slight sole constraint with the robot as shown in Figs. 4(b) and 5(b). Although the walking motion with wearing the exoskeleton robot is not exactly the same as that without wearing the exoskeleton robot, the walking motion with the robot is assumed to be similar to the natural walking motion in this study.

B. Experiment 2

The results of the second experiment are shown in Table II. There are three kinds of results: “recover”, “support”, and “fall down”. Here, “support” means the motion that the subject grabbed the handrail without losing balance when the external disturbance force was given. As a result, fall accident motion was not induced with the external disturbance force of forward direction. In the case when the external disturbance force was given in the forward direction, the hip flexion angle was significantly increased and the knee flexion angle was restricted in the swing leg.

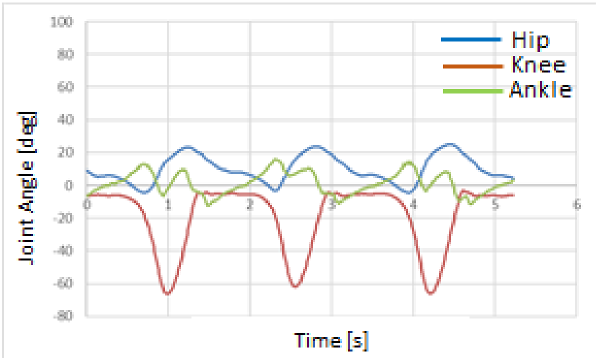


(a) Joint motion

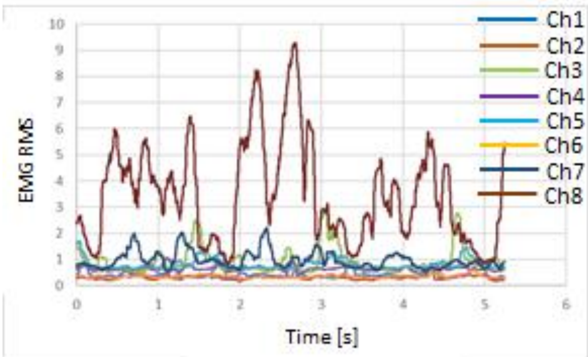


(b) EMG signals

Figure 4. Result of the left leg with the robot in Experiment 1.



(a) Joint motion



(b) EMG signals

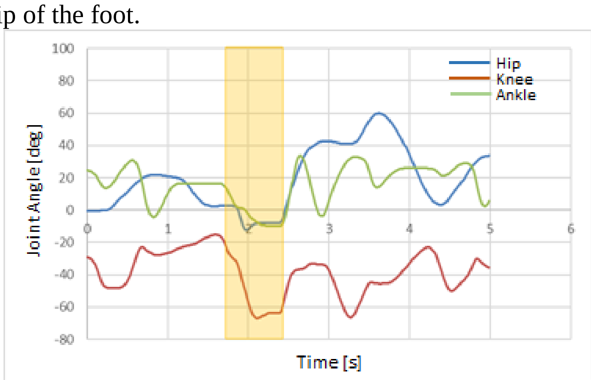
Figure 5. Result of the left leg without the robot in Experiment 1.

In the case when the external disturbance force was given in the backward direction, fall accident motion was generated only when the duration of the external disturbance force was long enough and also the amount of that was large enough. When the external disturbance force was given in the backward direction, the hip flexion motion was restricted and the knee flexion angle was slightly increased in the swing leg.

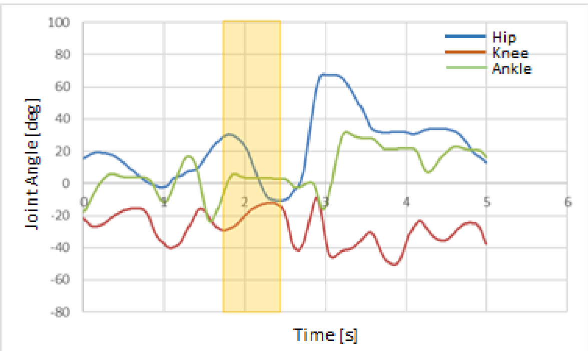
TABLE II. RESULTS OF EXPERIMENT 2

Subject 1				Subject 2			
Amount of Force [N]	Timing [%]	Duration [ms]	Result	Amount of Force [N]	Timing [%]	Duration [ms]	Result
8	72	180	Recover	9	11	480	Recover
12	24	700	Recover	16	47	390	Support
13	52	430	Recover	17	28	450	Recover
14	14	700	Recover	19	65	200	Recover
16	39	250	Recover	20	34	140	Recover
-8	48	520	Recover	-8	10	600	Recover
-13	31	590	Recover	-18	14	200	Recover
-15	10	270	Recover	-19	70	210	Recover
-15	44	480	Recover	-20	5	450	Support
-20	15	500	Support	-21	12	210	Recover
-21	17	250	Recover	-23	65	240	Recover
-25	57	370	Support	-29	17	100	Recover
-31	51	480	Fall down	-32	42	370	Recover
-33	31	400	Recover	-37	16	490	Recover
-37	62	280	Recover				

In the case of recovery motion when the external disturbance force was given in the backward direction (amount of the force was -13N, timing was 31%, and duration was 590ms), the tip of the foot of the swing leg (left leg) went up about 40 mm while it was moving forward and then down to the ground. This is similar to the elevating strategy [18][19] which occurs during the recovery motion from a trip since this disturbance force is similar to the stumbling force. The lower-limb motion and the upper-limb motion during the experiment is shown in Fig. 6 and Fig. 7, respectively. As shown in the figures, the hip joint motion was disturbed and the knee joint motion was increased in the swing leg to raise the tip of the foot.



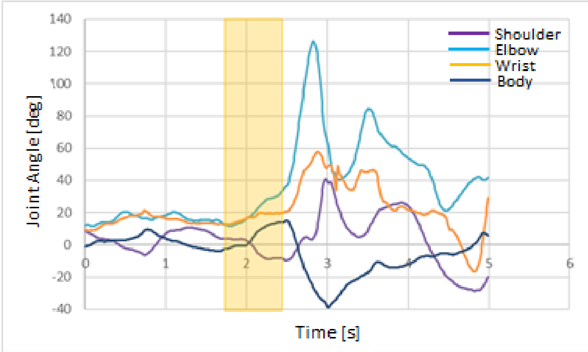
(a) Left leg (disturbed leg)



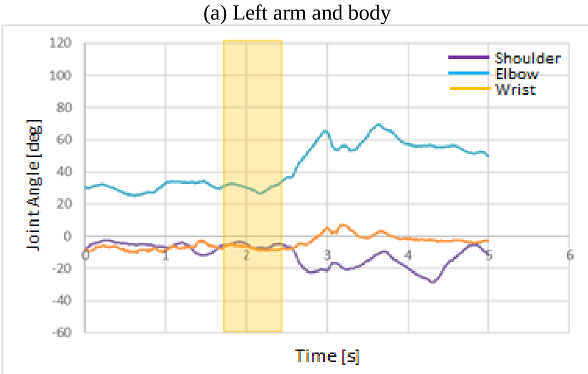
(b) Right leg

Figure 6. Result of the lower-limb motion in Experiment 2.

The angular momentum is important to recover the balance [20][21]. Both the lower body and the upper body react to compensate for the change of angular momentum after the disturbance is removed, although the lower-limb exoskeleton robot cannot modify the upper body motion. In the recovery motion, the arm of the swing leg side was raised just after the swing leg went down to the ground.

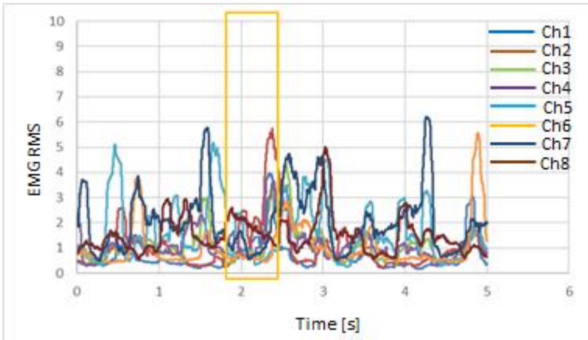


(a) Left arm and body

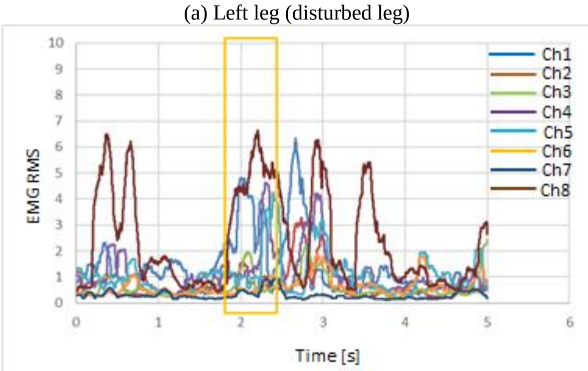


(b) Right arm

Figure 7. Result of the upper-limb motion in Experiment 2.

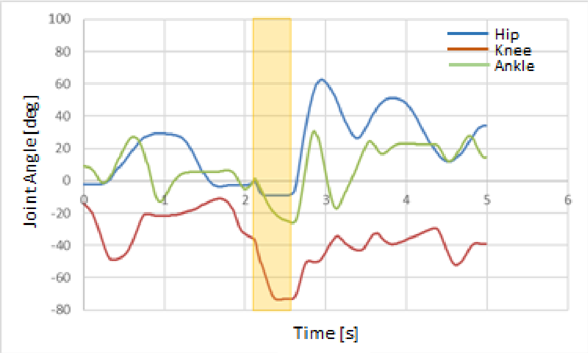


(a) Left leg (disturbed leg)

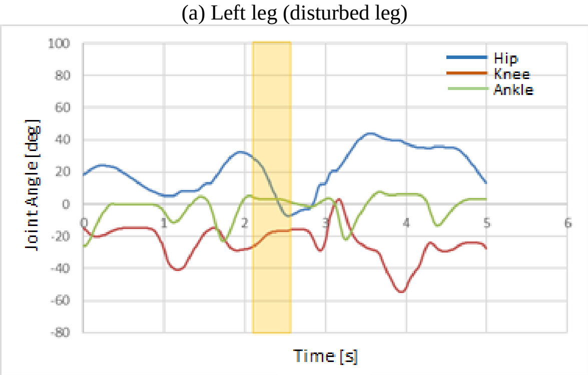


(b) Right leg

Figure 8. Result of the lower-limb EMG signals in Experiment 2.

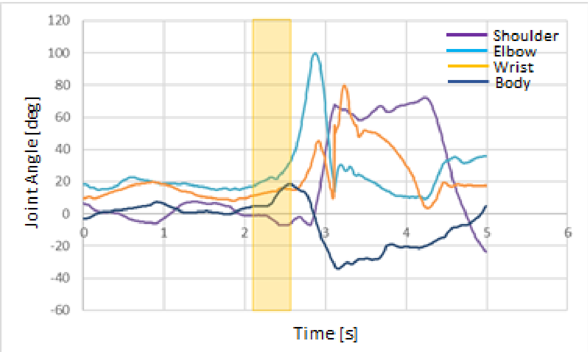


(a) Left leg (disturbed leg)

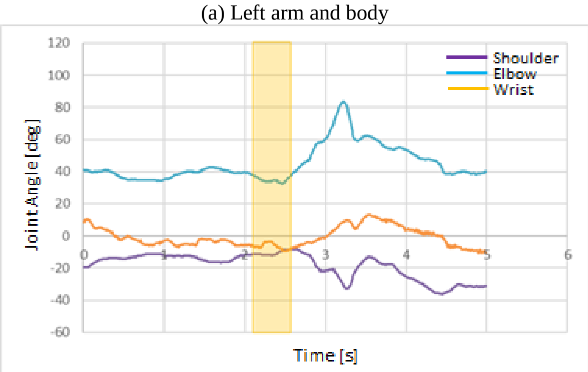


(b) Right leg

Figure 9. Result of the lower-limb motion in Experiment 2.



(a) Left arm and body



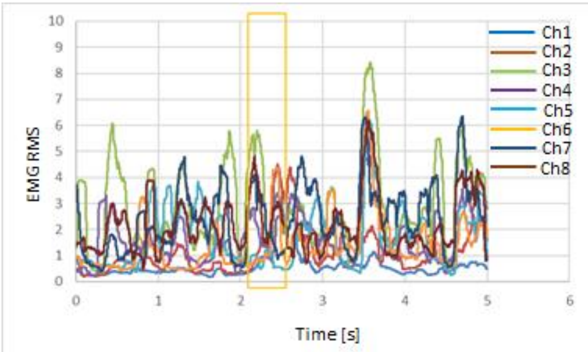
(b) Right arm

Figure 10. Result of the upper-limb motion in Experiment 2.

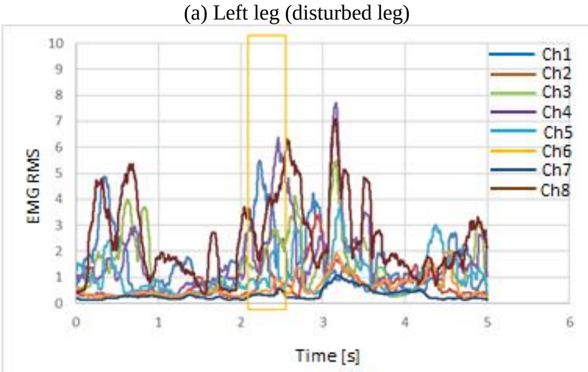
Fig. 8 shows the EMG signals of the lower-limb during the experiment. In the recovery motion, EMG signals of chs.1-4 in the swing leg were increased to compensate for the angular momentum change after the external disturbance force was turned off. EMG signals of all muscles in the support leg were increased during the disturbance. That means impedance of the support leg is increased to make the recovery motion.

The experimental results show that fall down motion is generated if certain amount of external disturbance force is given to the backward direction for certain duration at certain timing. In the case of fall down motion (amount of the force was -31N, timing was 51%, and duration was 480ms), the tip of the foot of the swing leg (left leg) just went up about 100 mm without moving forward and then down to the ground. The lower-limb motion and the upper-limb motion during the experiment is shown in Fig. 9 and Fig. 10, respectively. As shown in the figures, the hip joint motion was disturbed and the knee joint motion was increased in the swing leg to raise the tip of the foot. The left arm was raised just after the external disturbance force was given to the subject to compensate for the angular momentum change. However, those compensations were not enough to prevent the fall accident motion.

The analyzed results suggest that the swing leg is used to cancel the angular momentum change and the impedance of the support leg is increased to generate the recovery motion in the lower-limb exoskeleton robot when unexpected disturbance force is given to the swing leg in the backward direction.



(a) Left leg (disturbed leg)



(b) Right leg

Figure 11. Result of the lower-limb EMG signals in Experiment 2.

Fig. 11 shows the EMG signals of the lower-limb during the experiment. In the recovery motion, EMG signals of chs.1 and 2 in the swing leg were increased to compensate for the angular momentum change after the external disturbance force was turned off. EMG signals of all muscles except ch. 7 in the support leg were increased during the disturbance to increase the impedance of the support leg, although they were not enough to prevent the fall accident.

V. Conclusion

In this study, a method to use the lower-limb exoskeleton robot in order to generate the human fall accident motion is proposed to analyze the recovery motion and the fall accident motion. The analyzed results suggest that the swing leg is used to cancel the angular momentum change and the impedance of the support leg is increased to generate the recovery motion in the lower-limb exoskeleton robot when unexpected disturbance force is given to the swing leg in the backward direction. The results of this study can be used to provide the fall prevention algorithm in the lower-limb power-assist exoskeleton robot. Furthermore, the results can be used for physical training for elderly persons to prevent falling accident.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

K. Kiguchi made the research plan and wrote the paper. K. Noda carried out the experiments and analyzed the data. All authors had approved the final version.

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