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Development of a Walking Dummy Reproducible Fall Sign Patterns of Wearable Walking Support Devices

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***Abstract*—Typical fall sign patterns of the wearer of a wearable walking support device were extracted by walking experiments, and, to realize these typical fall sign patterns, a lower body walking dummy with a dummy cut-off mechanism was developed. The wearable walking support device as the test object is fitted on the walking dummy. This dummy is held in the upright position by a restraint, and made to walk on a treadmill.**

I. Introduction

The usefulness of a wearable walking support device has been increasingly recognized, but instability and measures to counter fall during the time when device wearer is walking have remained as issues to be fixed for the practical realization of the device [1]. In preparation for the risk of fall carried by the wearable walking support device, the device side is provided with fall sign detecting function and fall avoidance / motion stop control function, and the human side is provided with fall avoidance motion (wearer) and support motion (assistant) [2]. However, the risk of fall and these human protections are not evidently corresponded to each other, and the standardization of human protection from falling has not been in progress. Particularly, as to the fall (crisis) sign detecting function, a method of evaluating at which timing the unbalanced gait state and disordered walking rhythm of the device wearer should be detected has not yet been established.

Here, it is necessary to test whether the fall sign detecting function emits detection signal at an early timing before fall occurs, and verify the validity thereof. However, because it is difficult to uniformize test conditions when a human actually wears the wearable walking support device and to conduct the subject test itself, a walking dummy, which can realize the walking state in the wearable movement support device, is introduced.

This paper reports that the authors have extracted typical fall sign patterns and developed a walking dummy, which can reproduce these typical fall patterns.

II. Analysis of Fall Patterns with Exoskeletal Walking Support Device

A. Walking by Exoskeleton Wearers

To decide the specifications of the walking dummy, it is necessary to extract typical fall sign patterns of a walking support device wearer. To suit this necessity, it was decided to examine fall sign motions to be reproduced by the walking dummy from the observation of the actual gait of the device wearer. Accordingly, the observation was made with the approval of the Ethical Review Board of the National Institute of Occupational Safety and Health.

As a target device, ReWalk™ designed to be a walking trainer for lower limb paralyzed persons was used. This exoskeletal walking support device senses angles between the body trunk and the thigh axis with an inclination sensor, and controls the swinging out of the swing leg, while the device wearer can stand up, sit down and walk using a crutch. In the event of overload, prescribed time expiration (3 seconds by default) or excessive body axis inclination (17 degrees by default) caused to the drive system of this device, an alert is issued or control over the drive system is stopped [3], but motions of posture restitution or fall prevention by the very device wearer are not so promising.

In the measurement of walking, 5 normal men in their 50s loaded with a weight or a supporter to limit the motion range of their limbs in a simulation of aged persons were made to take a walking exercise with a Lofstrand Crutch, and then repeat 6 types of walking 3 times, including straight walking on a flat surface and upward/downward walking on a slope, in the state of being suspended as shown in Fig. 1. Since walking while wearing the device consumes physical strength unexpectedly, total number of walking was set as the maximum number of times that the device wearers could walk without fatigue after practicing until they could walk without assistance. These six types of walking assume walking states in which the

Walking of ReWalk wearer

i. Go straight while prodding both crutches at the same time (4m flat plane)
ii. Go straight while prodding both crutches at the same time (Change stride once)
iii. Go straight while prodding the left and right crutches alternately
iv. Go straight while prodding the left and right crutches alternately (Change crutch prodding position once)
v. Climb up from below the slope (5 degrees, 3m long) while prodding the left and right crutches alternately
vi. Go down from the slope while prodding both crutches at the same time

State of walking vi

Figure 1. Observation of the fall process during walking.

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device wearers normally train, and during these walks, the processes leading to the wearer's spontaneous near-fall were observed. Incidentally, there was little effect of slipping between the walking surface and the soles of shoes worn by the device wearers on the measurement.

B. Typical Fall Processes Based on Walking Observation

Among total 90 times of walking by 5 device wearers, 18 times per device wearer, a significant change in posture to the extent that it presumably ran into fall was observed at frequencies as follows: 0 times by one device wearer, one time by one device wearer, 2 times by 2 device wearers, and 3 times by one device wearer. The average time for 3 times by one subject to complete walking was about 1.5 times longer than for 0 times by one subject. The breakdown of the observed false step phenomena are shown in Table 1. Having analyzed the walking accompanied by such a posture variation as shown in this table, there was one case of swaying sideways around the stand, and all other cases of swaying after the swing leg landed down. In the latter cases, there were 2 times of lateral false step upon the landing of the swing leg, and other false steps were due to the sway of the body axis upon the landing of the swing leg. The analysis results of the case development of lateral false step upon the landing of the swing leg are shown in Fig. 2, and the analysis results of the case development of other false steps due to the sway of the body axis are shown in Fig. 3.

According to the scenario of running into fall shown in Fig. 2, in shifting from the left leg landing to the right leg landing, the subject made a false step, inclined to the left side, and finally tilted significantly forward (the forward tilt angle was 34 degrees, which could not be supported without the suspension system). From this, it is understood that if stable 3-point landing is not secured when the crutch is prodded, the subject falls into a situation where only one leg is loaded, and if the subject breaks down the balance at this time, the next

TABLE 1. FALSE STEP PHENOMENA DURING WALKING BY WEARER OF WEARABLE WALKING SUPPORT DEVICE (REWALK).

Walking form	Scenario leading to posture change	Number of times
Go straight on the flat plane (simultaneous prodding of both crutches)	When landing on the swing leg, the subject stumbles so that both feet are aligned, and it sways greatly by pivoting around the stand that had landed earlier.	2
	When the swing leg is swung out, the subject sways greatly sideways around the stand that had landed earlier.	1
Go straight on the flat plane (Alternate prodding with one crutch)	When the swing leg lands, the subject stumbles so that both feet are aligned, and pivots around the landed swing leg to rotate and sway greatly.	1
	When the swing leg lands, the subject sways greatly sideways around the landed swing leg.	2
Up the slope (Alternate prodding with one crutch)	When the swing leg lands, the subject stumbles so that both feet are aligned, and pivots around the landed swing leg to rotate and sway greatly.	2

crutch re-prodding is too late to prevent fall. On the other hand, according to the scenario of running into fall shown in Fig. 3, the subject landed the right leg but with a shorter step length, then the subject inclined leftward while pivoting clockwise on the right toe, and ended up in tilting significantly forward. In landing, when the step length was short, the subject stood with both feet in the aligned state and made a false step. In this case, the subject was apt to run into pivoting on the toe of either foot, and the subject made a late motion of crutch re-prodding and excessively broke down the balance before resuming the static

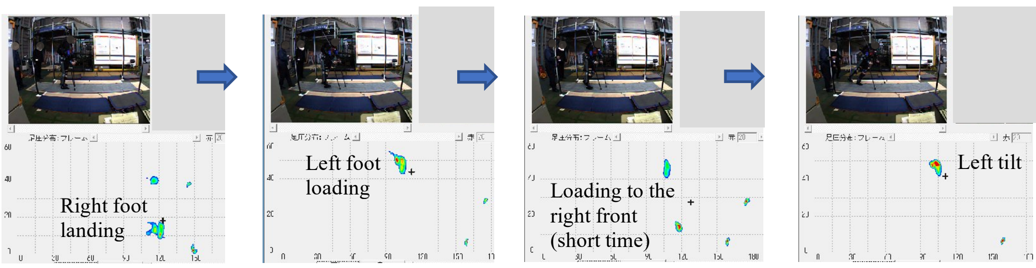

Figure 2. Analysis results of wobbling while walking by the ReWalk wearer.

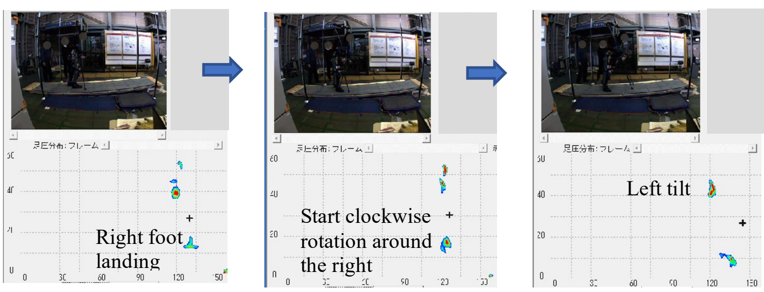

Figure 3. Analysis results of wobbling after pivoting during walking by the ReWalk wearer.

position. For aged persons in particular, because of and to the extent of a narrower ankle motion range, the possibility of their false step is higher. Furthermore, in the case of ReWalk, the fall sign detecting function and the overload detecting function compel alarm issuance and upright position resumption control, but these functions are antagonistic to motions of posture restitution or fall prevention by the device wearer, and the device wearer might break down the balance. However, this concern could be mitigated by proficiency.

In addition to the above observed 3 patterns, it was also assumed in the risk assessment of the wearable walking support device [4] that the device could suddenly stop operation during walking, and the device wearer might break down the balance in the state of one leg landing.

III. Development of Walking Dummy

A. *Basic Specifications of Walking Dummy*

The wearable walking support device, which is the test object, is fitted on the walking dummy. Then, the walking dummy is held in the upright position by a restraint, and made to walk on a treadmill. Since the walking dummy has such a form, it does not control the autonomous walking of the biped robot, but simply sets the trajectory of each joint of the dummy in advance and walks at a specific stride and speed.

This walking dummy is designed based on the standard lower limb dimensions of men in their 60s, and equipped with a hip joint and knee joints and power units with angle detecting function, can reproduce the dynamic gait by repeating step motions alternatingly from side to side on the treadmill. Then, while the walking dummy being in walking motions, the restraint is cut off, and thereby such an unstable state as seen in running into fall posture (i.e., typical fall sign pattern) is created. Fall sign detection signal then emitted from the wearable walking support device is recorded together with the gait state of the walking dummy. Here, the cutting off of the restraint and the stopping of the treadmill operation are programmed so as to be interlocked.

Based on the results of fall pattern analysis using the exoskeletal walking support device, the following 3 patterns were set as typical fall sign patterns:

1) Body axis inclination due to gravity shift in the dynamic state during continued walking
2) Walking dummy stopping with both feet in the aligned state due to short step length or false step when the swing leg lands (power OFF)
3) Walking dummy stopping with the swing leg in the air (device power OFF)

The pattern 1) corresponds to the process of lateral swaying around the stand while swinging the swing leg or the landed swing leg, and the pattern 2) corresponds to the process of rotating and swaying the body axis after the swing leg lands. On the other hand, in the pattern 3) extracted from the risk assessment results described above, the process of reaching the body axis inclination on the landed leg axis is the same as in the pattern 1), except that the swing leg is fixed. And although the probability of occurrence is low among 3 patterns, the pattern 3) was adopted because it is the most difficult to avoid a fall and serious harm is expected.

To realize the above 3 patterns with a walking dummy, patterns 2) and 3) can be reproduced by the motion (power) stopping of the walking dummy or wearable walking support device. On the other hand, pattern 1) can be reproduced by restraining the walking dummy for which the eccentricity of gravity has been caused beforehand, then making the restrained walking dummy walk, and then releasing the restraint from the walking dummy at some timing.

Other necessary conditions are set as follows:

- The body axis inclination should be caused by the entire inclination and gravity shift on the lower back due to the stopping of the legs during the walking motion.
- The gravity shift on the lower back should be caused by mass eccentricity due to the fixed weight.

TABLE 2. Main Specifications of Walking Dummy.

Walking dummy	Femur length: 422mm, Lower leg length:353mm Mass approx.: 60kg Hip / knee joints:100W servo motor, belt drive Ankle joint: Free (spring return) Eccentric weight: 5kg (waist)
Restraint (dummy cut-off)	Restraint: Maintaining a standing posture during dummy walking (air pressure balance & damper) Cut-off mechanism: Coupling / releasing between dummy and restraint by electromagnetic solenoid
Treadmill	Commercial product (start / stop is linked to dummy walking)

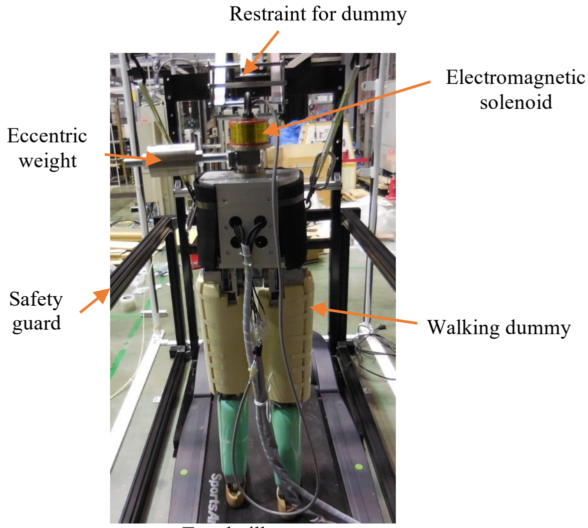

Figure 4. Walking dummy and peripherals.

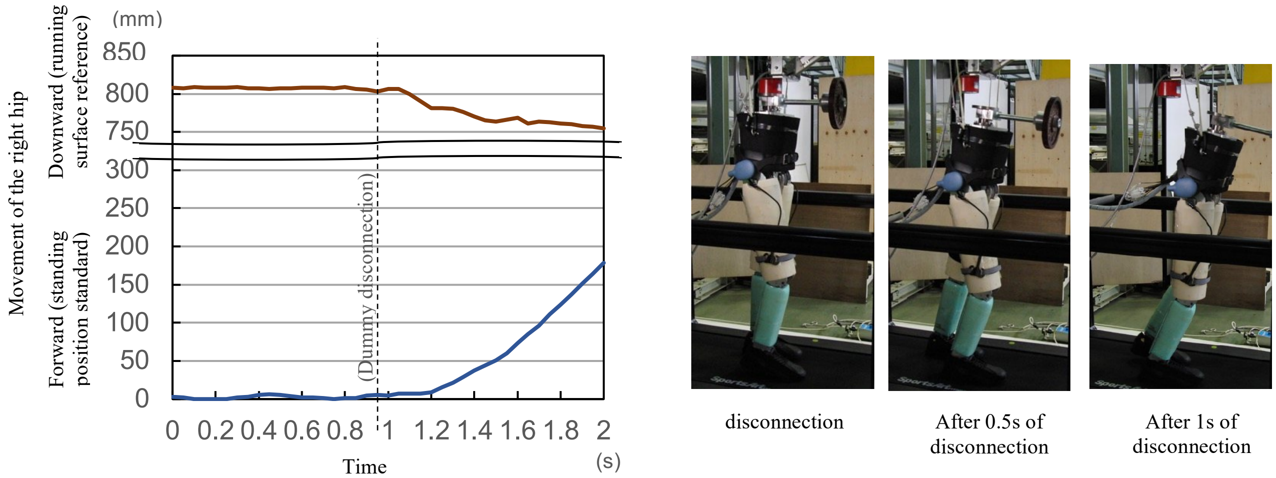

Figure 5. Observation example of fall sign movement of walking dummy (typical fall sign pattern 2).

The basic specifications of each main composing element are shown in Table 2, and the peripheral devices of the walking dummy are shown in Fig. 4.

B. Reproduction of Sign Motions Running into Fall

Whether the lower body walking dummy was able to reproduce the above-described fall sign motion patterns 1) – 3) which ran into the fall was ascertained by experiment.

First of all, the walking cycle of the walking dummy and the running speed of the treadmill were synchronized with each other. Then, it was confirmed that the subject was forced to take an unstable posture when the swing leg of the walking dummy was stopped. At this time, it was difficult to control the direction in which the walking dummy was inclining, and such a directional control was dependent on the position of the swing leg and the timing of stopping the treadmill.

Secondly, both feet stopping in the aligned state at the time of landing due to short step length or consequent false step was able to be reproduced by setting the step length of the walking dummy and stopping the motion when the swing leg landed. However, the control of the direction in which the walking dummy was inclining following the false step was problematic as above described.

To reproduce the body axis inclination due to gravity shift during walking, because an active gravity shift mechanism was not made ready this time, the walking dummy loaded with a fixed eccentric weight on the lower back was held in the stable posture by a restraint, and this restraint was cut off during walking to realize the inclination of the body axis. The optimum combination of the mass and setting position of this eccentric weight were groped for by trial and error, and arbitrary body axis inclination was able to be realized almost steadily.

As an example, an eccentric weight was attached to the front side of the lower back of the walking dummy, and at the moment when the right swing leg landed on the treadmill with a short step length, the treadmill running was stopped. The results of the observation of this process are shown in Fig. 5. At 1s in this figure, the restraint was cut off from the walking dummy. It is understood from this that the walking dummy inclined forward through the influence of the weight. Here, the running surface of the treadmill was controlled to stop at the instant when the restraint was cut off, but a slight time lag and overrun were caused until the treadmill completely stopped.

IV. Conclusion

The typical fall sign motions of the wearer of the exoskeletal walking support device were investigated, and a walking dummy which was able to reproduce the fall sign motions without depending on manual participation was developed. With this dummy, it is now possible to observe the process from walking motions to fall. Furthermore, the authors are proceeding with the presetting of fall sign patterns, and the creation of interlocking patterns of the stopping of the walking dummy, stopping of the treadmill running and electromagnetic cutting off of the restraint, and will try to reproduce walking patterns with various exoskeletal walking support devices on the walking dummy.

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