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# Strength Testing Machines for Wearable Walking Assistant Robots based on Risk Assessment of Robot Suit HAL

Cota Nabeshima, Hiroaki Kawamoto and Yoshiyuki Sankai

**Abstract**—The safety of wearable walking assistant robots (W2ARs) is expected to be guaranteed as they are spreading. From our experience of the risk assessments on Robot Suit HAL, we assume that the mechanical angle stoppers and appropriate assembling are inherent safety measures for the W2ARs. These measures prevent the hazardous situations: excess assistance and collision with floor or wall. In this paper, we develop the testing machines to prove their strength. They have the weights imitating a leg or a whole body and simulate cyclic impulsive load during walking by exploiting free fall. We hope this paper helps to develop safer W2ARs and to establish safety standards of the W2ARs.

## I. INTRODUCTION

The decade after the first prototype of Robot Suit HAL was developed [1], [2]. CYBERDYNE Inc. achieved the practical use of Robot Suit HAL for Well-being [3]. Robot Suit HAL is categorized as wearable walking assistant robots (W2ARs); Lokomat of Hocoma AG [4] and Walk Assist and Mobility Devices of Honda Co.,Ltd. [5] are within the same category.

We are now at the dawn of the industrialization of the W2ARs. The manufacturers of the W2ARs are socially demanded to present the safety of their products to reassure their users. It could be an easy way to comply with the adequate safety standards.

The international safety standard ISO 13482 [6] is currently under discussion. It will define the safety requirements for Personal Care Robots (PCRs) including the W2ARs as a Type C standard of ISO 12100 [7].

ISO 12100 defines general safety requirements for machines; it is oriented to machines anchored in factory environments. ISO 12100 ensures machines are stable in the environment, and implement emergency stop devices or controls such as mechanical brakes. Guards or fences are also recommended to isolate people from “hazardous” machines.

The PCRs’ applications are intrinsically different from those of the factory machines. The PCRs might be unanchored to work in the living environment. They could be designed low-powered and human-sized; that is, the protective measures for the PCRs are surely different from the factory machines. This issue defines the direction of ISO 13482 to generally override ISO 12100.

Whatever ISO 13482 becomes, the safety of the whole system should be achieved by inherent safety measures—separation of hazardous source. That is, risk assessment

is necessary to determine what protective measures are practical.

In this paper, we first summarize our previous paper [8] to give qualitative risk assessments of the W2ARs (Sec.II). Based on the risk assessments, We identified that the mechanical angle stoppers and appropriate assembling are suitable protective measures for the W2ARs as the inherent safety measures (Sec.III).

In Sec.IV, we propose and develop the strength testing machines for the measures, where cyclic colliding force during walking could be applied to a W2AR. To evaluate the testing machines, we perform the experiments with Robot Suit HAL for Well-being.

We hope this paper will be helpful to present the safety of the W2ARs. Moreover, we would be honored if it contributes to expand the market of the PCRs.

## II. RISK ASSESSMENTS

In our previous paper [8], qualitative risk assessments for the W2ARs were addressed based on our experience as the manufacturer of Robot Suit HAL. Here we summarize the paper to explain why we need the strength testing machines and what type of them to be developed.

The risk assessments must be qualitative due to a lack of similar products to the W2ARs in the market. We defined a basic functionality of the W2AR in [8] as,

The W2AR actively applies force or torque to the body consisting of its wearer and itself equipped with one or more actuators to assist the wearer to walk.

We believe this definition is applicable to the existing W2ARs.

As for the W2ARs, there are three discriminative points from the factory machines:

- the wearer and the robot move monolithically;
- the wearer is both the controlling subject and controlled object; and
- the actuating power is less than or comparable to the human’s power seen in daily life.

We also note the W2ARs are never developed for cutting, bending, grinding, pressing or drilling operations in contrast to the factory machines. We mean the W2AR do not include “power-augmenting” robot such as [9] or [10].

We took a top-down approach for the risk assessments. From the usage of the W2ARs, we listed the major hazardous situations that harm the wearer as,

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- H1: excess assistance: excess force/torque, velocity/angular velocity or position/angle beyond the wearer's mechanical tolerable limits, and
- H2: collision with the floor or the wall by losing balance.

This list does not cover all hazardous situations. The other well-known and possible hazardous situations were also listed: e.g. touching a hot part, touching an electrically active part, pinching a finger in a joint, dropping of a battery, and so on.

The hazardous situations H1 and H2 are consequence of possible hazards. Poor control programs, poor motor performance or poor brace design would lead kinematic incompatibility and result in H1 or H2.

To identify the risk level, we defined risk matrices as Table I and Table II. We identified the risk level (RI, RII or RIII) based on avoidability from hazardous situation, frequency of hazardous situation, and severity of harm, which are referred in IEC 61508-5 [11].

We exploited our experience as the manufacturer of Robot Suit HAL and identified the initial risks of the hazardous situations assuming no protective measure. The identified initial risks are shown in Table III with comments. In the table, we indicate ID of a hazardous situation by Hx, the frequency level by Fx, the avoidability level by Ax, the severity level by Sx and the risk level by Rx.

In Table III, there are ranges of levels to incorporate the cases of the other W2ARs. All levels of avoidability, frequency and severity could be high without any protective measure.

### III. SAFETY MEASURES FOR W2ARS

We exemplified what protective measures are possible for the W2ARs in [8]. Here we classify them into inherent safety measure, functional safety measure or operational policies.

Here we only show the protective measures for the specific risk to the W2ARs described in Sec.II. The existing safety standards (e.g. [12] or [13]) are informative for the possible measures to reduce the other risks that are typical in machines, electrical devices and software.

Table IV and Table V show the possible protective measures. The second column in each table is the factor expected to be reduced by the corresponding measure, where F is the frequency level, A is the avoidability level and S is the severity level.

Placement of actuators at each joint of the wearer and mechanical limits of the angle are straightforward ways as the inherent safety measures to prevent the excess assistance. These measures are verifiable by maximum output test of the actuators and strength test of the mechanical limits of the angle (Sec.IV).

The mechanical limits of the angle might be a source of a new hazard. The limits can reduce the excess situation; meanwhile the impact force transmission might occur to its wearer. Although this additional risk will end up residual, the risk might be low and acceptable in return to the prevention of the excess assistance.

TABLE I  
MATRIX TO DERIVE EXPOSURE LEVEL.

		Avoidability			
		A1	A2	A3	A4
Frequency	F1	E1	E1	E1	E1
	F2	E1	E1	E2	E3
	F3	E1	E2	E3	E4
	F4	E2	E3	E4	E4

Avoidability from hazardous situation is as,

- A1: "easy,"  
A2: "possible,"  
A3: "difficult,"  
A4: "impossible."

Frequency of hazardous situation is as,

- F1: "never,"  
F2: "rare,"  
F3: "occasional,"  
F4: "often."

TABLE II  
MATRIX TO DERIVE RISK LEVEL.

		Exposure level			
		E1	E2	E3	E4
Severity	S1	-	-	-	-
	S2	-	-	RI	RII
	S3	-	RI	RII	RII
	S4	RI	RII	RIII	RIII

Severity of harm is as,

- S1: "no injury,"  
S2: "curable or minor injury"  
e.g. cut or scrape of skin,  
S3: "incurable or serious injury"  
e.g. loss of fingers or limbs,  
S4: "mortal injury."

The collision with a floor also cyclically occurs on foot during walking. That could be a major reason for the W2ARs to fail, and a hazard source to lead unbalance and, finally, hazardous collision between the wearer and floor or wall. We believe that the strength of structure of the W2ARs only prevent the hazard and resultant hazardous collision.

Using safety equipments such as a helmet, knee supporters and elbow supporters are reasonable in analogy with skiing, skating or skateboarding. These additional items tend to be forgotten to use by the users. It seems more acceptable for the users' convenience to use a body weight support system, a walker, a cane or safety wheels.

The functional safety measures listed in Table IV and Table V seem hard to implement and verify. The balance controlling methods of the W2AR and its wearer have not yet been established. It is also critical to account for the latency of the control feedback. Even without these functional safety measures, we believe that the inherent safety measures and operational policies are sufficient to guarantee the safety of the W2ARs.

TABLE III  
INITIAL RISKS WITHOUT ANY PROTECTIVE MEASURE.

H1	Excess assistance
F - 4	If restraint devices are used (e.g. straps) to transmit power to the wearer, the excess assistance is often possible.
A - 4	If the restraint devices are hard to detach instantly, it could be impossible to avoid the situation.
S - 3	If potential output of an actuator is far exceeding the wearer's tolerable limits, it could cause an injury (e.g. a sprain) of the joint.
R - II	It might not be acceptable.

H2	Collision with floor or wall
F - 3	If instability of balance is exploited to walk with no extra walking aid, it could happen as frequently as without the W2AR.
A - 4	If the wearer is not able to take a defensive action, the collision could not avoidable.
S - 3	If the head of the wearer is collided, it could lead to a serious injury.
R - II	It might not be acceptable.

#### IV. STRENGTH TESTING MACHINES

We have to verify the performance of the feasible protective measures listed in Sec.III. The verification methods for the other typical protective measures in machines, electrical devices and software are described in the existing safety standards.

In this section, we propose strength testing methods and machines of a mechanical limit of a joint angle and assembling, which are specific and not yet regulated for the W2ARs. Our methods and machines are able to simulate the forces during walking; i.e. impulsive, fluctuant and viscoelastic force during walking could be loaded to the W2AR as the strength tests.

##### A. Strength Test of Mechanical Limit of Joint Angle

We assume a mechanical limit of a joint angle is to confine joint motion in a tolerable range of the wearer. The concept of the testing method we propose for the limit is illustrated in Fig.1, where one end of a test joint is set in a stationary wall, the contact surface of limit is horizontally aligned, and a weight is fixed in the other end. Here we assume the W2AR has joint mechanisms each of which is separable as a single joint.

A test procedure is that the weight rises and falls due to the force of gravity. In this test, the impulse is a monotonically increasing function of the potential energy; therefore, parameters of the test could be the raised height (i.e. the raised angle and the length of the arm) and the mass of the weight. Those parameters should be determined for each W2AR based on the maximum angular velocity and the mass of whole (or a part) of the wearer and the W2AR.

TABLE IV  
POSSIBLE PROTECTIVE MEASURES FOR H1: "EXCESS ASSISTANCE"

H1: Excess assistance		
Type	Factor	Protective measure
Inherent safety measures	F	Place actuators at each joint of the wearer and mechanically limit the angle. Design maximum rating of actuators under wearer's mechanically tolerable limits.
	A	Mechanically dismount the W2AR from the wearer if beyond the limits.
	S	Design maximum rating of actuators under wearer's mechanically tolerable limits.
Functional safety measures	F	Controls force/torque, velocity/angular velocity or position/angle to keep under wearer's mechanically tolerable limits.
	A	Automatically dismount the W2AR from the wearer when the excess assistance is detected.
	S	Automatically stop the actuator's output instantly when the excess assistance is detected. Automatically stop the actuator's output instantly when the request from the wearer is input. (e.g. an emergency shutdown system)
Operational policies	F	Instruct the user how to adequately adjust the alignment of the W2AR and the control parameters.
	A	Instruct the user how to stop and dismount the W2AR.
	S	Instruct the user to use the W2AR with appropriate safety equipment to protect the joint of the wearer.

For instance, in case of a limit for a knee joint, the mass would be of the leg below the knee; the angular velocity might be less than that in daily life. The maximum angular momentum is calculated by the mass and the angular velocity; and it could be translated to a raised height.

We can suppose a success criterion for the test; e.g. how much angle overrun of the mechanical limit occurs after repeating the test a specified number of times. This number of times should be determined due to an application of each W2AR.

Fig.2 shows our developed testing machine, which equipped a knee joint of Robot Suit HAL for Well-being as a test piece. This testing machine moves its winch, lifts the end point of the weight and releases it by declutching. It

TABLE V  
POSSIBLE PROTECTIVE MEASURES FOR H2: "COLLISION WITH FLOOR OR WALL"

H2: Collision with floor or wall		
Type	Factor	Protective measure
Inherent safety measures	F	Embed an additional assistive device (e.g. a body weight support system, a walker, a cane or safety wheel) into the W2AR.
		Design and assemble the W2AR with the strength to the collision with a floor during walking.
	A	-
Functional safety measures	S	Design the W2AR itself as a protector with exterior covering the whole body.
	F	Control the balance with predicting the collision.
	A	Control avoidance behavior when the collision is predicted.
	S	Control protective behavior when the collision is detected.
Operational policies	F	Initiate an air-bag when the collision is predicted.
	F	Instruct the user to use an additional assistive device (e.g. a body weight support system, a walker, a cane or safety wheel) with the W2AR.
	A	-
	S	Instruct the user to use appropriate safety equipments: a helmet, knee supporters and elbow supporters.

also detects the overrun in case that the test piece is broken, and automatically stops the test.

We experimented the strength of the test piece with  $\pi/4$  [rad] raised angle and 20 [kg] weight. These values are determined ad hoc to test the testing machine. We performed two tests and the machine rightly fell the weight. After the tests, the test piece resulted in no failure and the limit was not overrun.

### B. Strength Test of Assembling

There is not yet standard technique to test the strength of assembling of a wearable structure (e.g. ankle braces) against impulsive and fluctuant forces during walking. It seems because the load is non-uniformly dispersed to the body of the wearer and the structure.

Fortunately, prosthetic legs with joints are analogous to the W2ARs. According to ISO 10328 [14], 1-4 [Hz] repetitive compressive forces are applied to the prosthetic leg with an alignment where bending moment is loaded on the mechanical limit of the joint angle. Its conformance is judged by resultant deformation and breaking. The applied force is

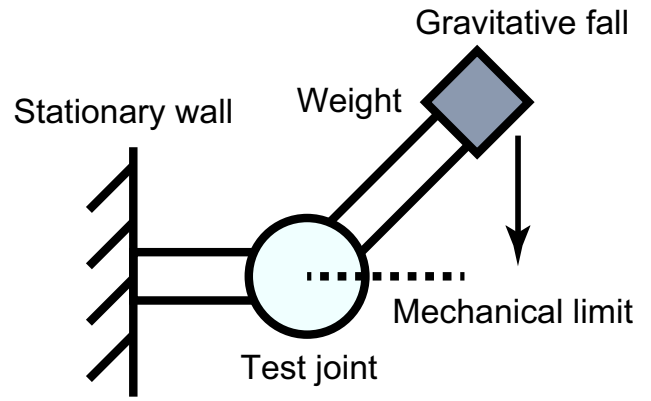


Fig. 1. The concept of the tester for a mechanical limit of a joint angle.

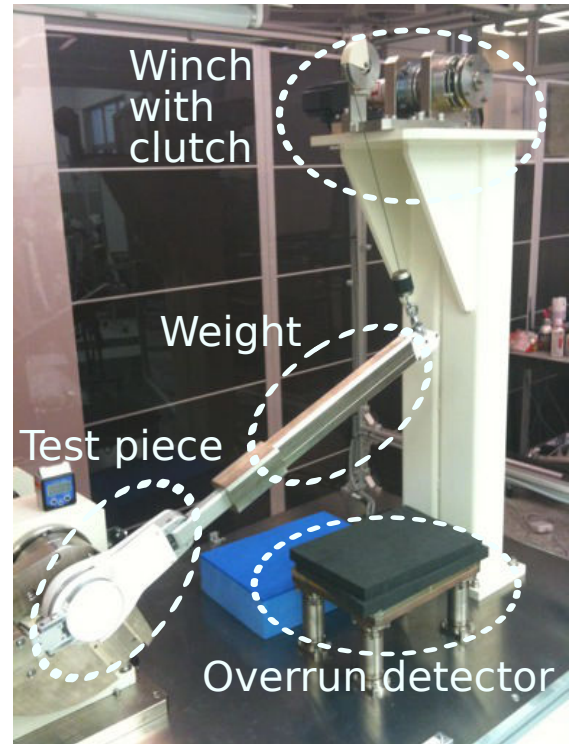


Fig. 2. The testing machine for a mechanical limit of a joint angle.

regulated to be 1,180-1,230 [N] 3,000,000 times under an 80 [kg] wearer.

These testing conditions are plausible for a structure to support the whole body weight of the wearer. The load during walking is estimated 1.6 times of the body weight<sup>1</sup>; and 3,000,000 times durability might assure 2 months operation with 90% reliability assuming that one leg does 5,000 steps a day under the exponential reliability function.

The problem in the case of the W2ARs is that the force dispersion coefficient to the body is nontrivial; therefore, required strength for the W2ARs might be much less than the prosthetic leg. The test methods are necessary to simulate repetitive compressive force applied to the W2ARs.

Intuitively, a test could be conducted by making another

<sup>1</sup>The peak of the floor reaction force during human's walking is up to 1.5 times of body weight according to [15].

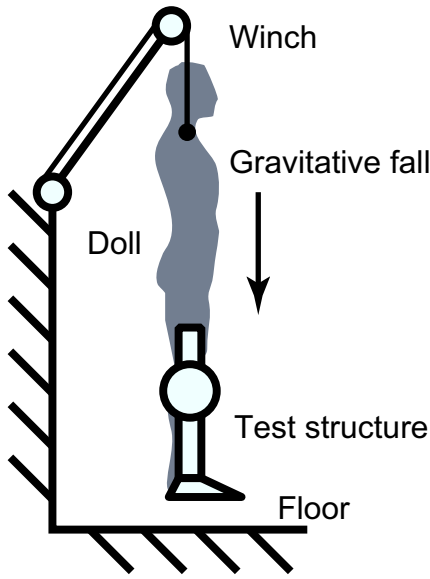


Fig. 3. The concept of the tester for the strength of assembling.

robot (doll) wearing the W2AR and walking. It seems, unfortunately, very difficult because control techniques to keep the doll walking in a long time are rarely available today.

The concept of the testing method we propose is shown in Fig.3. The W2AR is set to a doll in the same way as ordinary use; the doll has the weight, the size and the major (passive) DOF that imitate those of the wearer.

A test is performed by raising and dropping the doll. The test parameters are the mechanical structure of the doll and the raised height. The doll should be regularized for reproducibility of the test. A calibration process could determine the raised height.

We also propose the calibration process as, before the W2AR is set, the doll is dropped down from various height several times. When the floor reaction force upon landing is 1.6 times weight of the doll, the height at that time is used to raise the doll during the successive tests.

A success criterion for the test could be no failure after a specified number of falls. This number of times should be determined due to an application of each W2AR.

Fig.4 shows our developed testing machine, where the doll [16] equipped Robot Suit HAL for Well-being as a test structure. This testing machine moves its slider, lifts the doll and the test structure together, and fall it by declutching. It can adjust the raised height and measure the floor reaction force by the force sensor.

We experimented the strength of the test structure with 20 [mm] raised height. 2.8 [kN] floor reaction force were measured at the height during the calibration process. We estimated each leg was 1.4 [kN] loaded; i.e. 1.8 times weight of the doll. During 30977 times falls we performed, the machine worked without any problem and the test structure resulted in no failure.

Fig.5 is the frequency distribution of the floor reaction force obtained during the experiment. The mean of the

Lifting slider with clutch

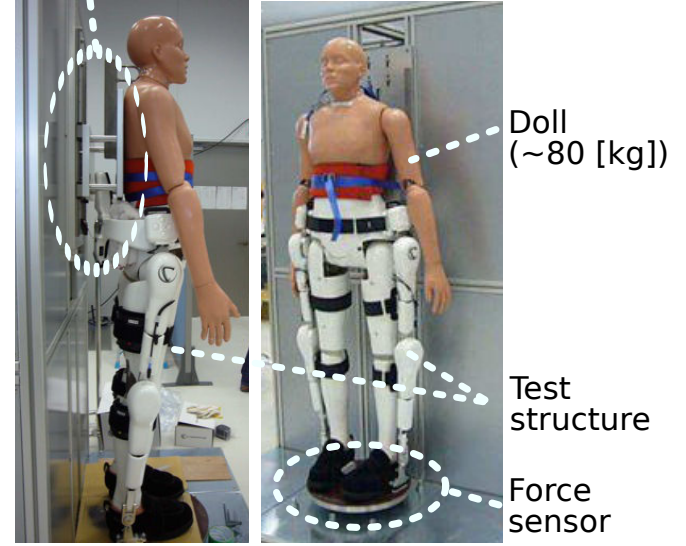


Fig. 4. The testing machine for the strength of assembling.

distribution was 2.88 [kN] and the standard deviation was 0.106 [kN]. The minimum force was 2.58 [kN], which was over 1.6 times weight of the doll.

This result indicates our proposal testing method can simulate the load during walking. By using this testing machine, the strength of assembling of the W2ARs could be evaluated only if they can be set to the doll in their ordinary use.

## V. DISCUSSIONS

The testing machines developed in Sec.IV are truly simple. The impacts applied on the structure of the W2AR are only in the major vertical direction.

We know the loads on the W2AR are more complex during actual walking. They could be multi-directional and multi-rotational; moreover, they also depend on the individual. Even with the state-of-the-art, they are harder to simulate in simple and regularizable methods.

Of course the “true” strength of the W2AR might not be tested or evaluated in other methods than the actual use or

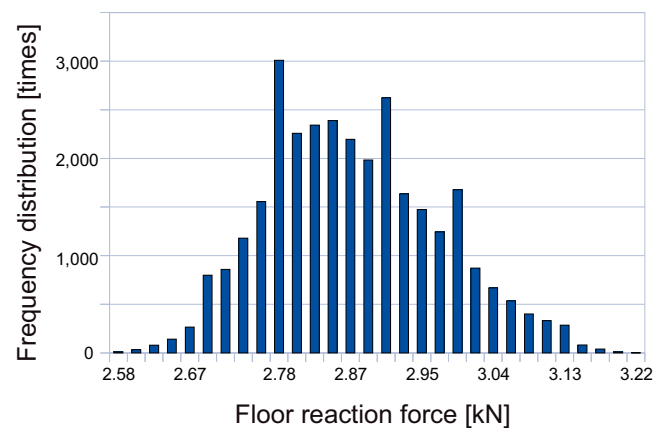


Fig. 5. The frequency distribution obtained by the experiment of the testing machine for the strength of assembling.

the track records in market; however in the early stage of the product, the simple tests to prove the minimal safety is pragmatic for its manufacturer. Our testing methods and machines developed in this paper are available for such tests.

If our testing methods and machines are applied, the manufacturer will be able to decompose the problem into the safety factor and the quality factor. This is the point to be required for a safety standard; the safety factor should be included in the standard and the quality factor should be a competitive domain.

In addition to the safety testing methods, we expect the standard testing methods for the performance of the W2AR become necessary in the near future. This will be an important research topic.

This paper focused on the safety testing of the W2ARs. In the normal usage, the wearer and the W2AR keep contact and are never collided. If we consider other PCRs e.g. with manipulators, the collisions with the human should be assessed. [17] and [18] could be suggestive advices to test such collisions.

## VI. CONCLUSION

We foresee personal care robots (PCRs) will have the potential to improve our lives. Especially, wearable walking assistant robots (W2ARs) seem up-and-coming. They could support our motor abilities.

Initially, the manufacturers are cautiously designing their PCRs to be safe. If their safety is acceptable to the users, their psychological hurdles might be dissolved, so that the PCRs will be widely adopted. However, the safety standards for the PCRs have not yet been established. The manufacturers inevitably have to take a principle methodology such as the risk assessments and test their protective measures in their own unique methods.

In this paper, we summarized our previous paper to show an example of the risk assessments and corresponding protective measures for the W2ARs. Especially, the excess assistance was an intrinsic hazardous situation of the W2ARs. It could be inherently prevented by a mechanical limit of a joint angle. The mechanical strength of assembling of the W2ARs is also inherent to prevent the hazardous instability.

It seemed necessary to test these inherent safety measures to prove the safety of the W2AR; therefore, we developed the testing machines. Our experiments show their availability to test the W2ARs. They were able to apply repetitive load simulating impulse during walking.

The new standard ISO 13482 [6] is coming, which originates in the safety standard for factory machines. Whatever ISO 13482 will require to the manufacturers of the PCRs, they have to design and present the safety of their products with the knowledge from literatures. We believe our papers and the testing machines will contribute them as the knowledge. We would like to see a variety of the PCRs whose safety is designed and verified.

In Japan, Robot Safety Center [19] was launched at Tsukuba in 2010 prior to other countries, which validates the safety of the PCRs. This activity will nurture a relationship

among users, certifiers and manufacturers. It will improve the safety of the PCRs.

## VII. ACKNOWLEDGMENTS

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