Relationships between Quantitative and Subjective Evaluations of Assistive Effect on Standing Function of the Smart Suit

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***Abstract*—The Smart Suit is a power assist suit that reduces the burden on the lumbar region by reducing the activity of the spinal column erector muscle and has a trunk stabilizing effect. The suit also has assistive effect on stabilizing human trunk motion by tightening the pelvis. By using this as prevention of work-related accidents, it leads to the elimination of labor shortages. However, for the smooth introduction of Smart Suit, it is important to match the objective auxiliary effect with the subjective auxiliary effect. In this study, we focus on the balance assistive effect of Smart Suit and clarify the objective support and subjective assistive effects.**

Keywords–Assist Tool; Standing Function; Quantitative and Subjective Evaluations.

I. INTRODUCTION

Japan has a rapidly aging population. According to the Annual Health, Labour and Welfare Report 2016 [1], the aging rate was 26.7% in 2015, whereas it was less than 5% in 1950. The aging rate is expected to increase, and one in 2.5 people in 2060 will be 65 or older. Thus, the working-age population supporting the elderly is decreasing and it is becoming difficult to maintain the labor force. To address this problem, one idea is to reduce the burden of labor, thereby reducing the risk of injury and illness and allowing people to work longer. KEIROKA technology reduces the physical burden without interfering with the movement of the worker. The Smart Suit [2][3] is an assistive technology used by various workers, including farmers, fishers, construction workers, industrial workers, and nursing care workers.

The Smart Suit is an assistive tool that uses a rubber belt to exert an assistive effect in a forward bending position. The suit reduces the activity of the spinal erector muscles by assisting the muscle force and stabilizes the trunk by increasing joint stiffness via the tightening force. However, there are individual differences in the exertion of the assistive effect and the agreement between the objective and subjective assistive effects. Therefore, the subjective assistive effect of the Smart Suit can indicate what the objective assistive effect of the Smart Suit feels like, allowing the efficiency of the suit to be improved. Understanding these relationships is expected to help the introduction and diffusion of Smart Suit. In this paper, we focus on the balance assistive effect of the Smart Suit and clarify the relationship between the objective and the subjective assistive effects.

II. RELATED WORKS

Although we measure the subjective assistive effect of the Smart Suit here, several studies have subjectively measured the work load. NASA-TLX (Task Load Index) developed by Hart et al. [5] is a widely used technique for measuring subjective mental workload. It uses a multidimensional construct to derive an overall workload score based on the weighted average of evaluations on six subscales: mental demand, physical demand, temporal demand, performance, effort, and frustration level. Subjective workload experience tasks, behaviors, and subject-related correlations are defined as a function of difficulty of manipulation within the experiment, various workload sources between experiments, and individual differences in workload definition.

Yamada et al. [6] proposed an assist system for subjective burden called Skill-Assist, which varies its mechanical impedance to give workers who have been working for many years a sense of achievement in being able to perform the skilled tasks they were capable of when younger again. A Skill-Assist control algorithm based on variable impedance control has been proposed.

The present study describes the relationship between subjective and objective assistive effects for the balance assistive effect of Smart Suit. However, we think that the results are relevant to other assist tools and workload support.

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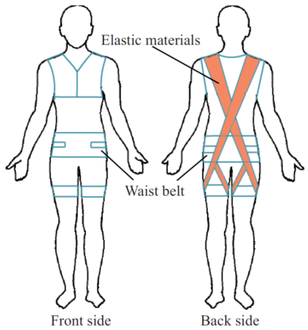

Figure 1. Schematic of elastic belts [2].

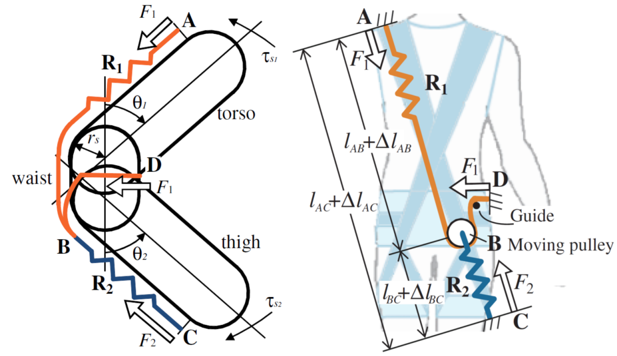

Figure 2. Assist mechanism of Smart Suit [2].

III. Assist Mechanism of Smart Suit

We describe the configuration of the Smart Suit and its effects. Figure 1 shows a schematic of the Smart Suit and Fig. 2 shows the assist mechanism. Elastic belts connect the thighs and shoulders to the back. The Smart Suit fits closely to the wearer's body and the assistive force is set according to the expected workload.

The elastic belt for the upper body, R_1, and the elastic belt for the thigh, R_2, are connected by a movable pulley at a point. The initial length of the path between A and C to the waist belt at point D after folding back at point B is the natural length of the elastic belt, and the change in path length when the wearer changes posture, Δl_{AC}, generates force F_1 at A and force F_2 at C. Assist torques τ_{s1} and τ_{s2} expand hip joint θ_1 and lumbar spine joint θ_2, respectively. The supporting torque reduces the wearer's joint torque and reduces the load on the muscles that move the joints. Simultaneously, force F_1 acts on the resilient waist belt at point D. F_1 increases the compression on the belt and lumbar spine at the tightening point. The combined torque τ_{s12} and force F_1 are given as

$$\tau_{s12} = \tau_{s1} + \tau_{s2} = \frac{6}{5} r_s k_s \Delta l_{AC} \quad (1)$$

$$F_1 = \frac{2}{5} k_s \Delta l_{AC} \quad (2)$$

where r_s is the moment arm of the elastic material and k_s is the coefficient of elasticity.

Equation (2) is derived from the balance of forces between elastic materials with a pulley configuration. The extended length of the entire line from shoulder to leg is divided by a ratio of 1:4 between the upper and lower elastic material.

According to Imamura, the rigidity of the trunk is increased and the posture is stabilized by force F generated during the forward bending posture [3]. In other words, wearing a Smart Suit exerts a sensory stabilizing effect and improves the stability of the entire body. And Imamura et al. presents an enhanced framework for evaluating an assistive effect of Smart Suit using a humanoid robot[4]. In this paper, we consider these assistive effects as balance assistive effects and perform subjective and objective evaluation.

IV. Evaluation of Standing Function Based on Virtual Light Touch Contact

We describe a Standing Function Evaluation System [7] used for quantitative measurement of the balance assistive effect of the Smart Suit. The Standing Function Evaluation System uses Virtual Light Touch Contact (VLTC) [8] devised by Sakata et al. Maintaining a standing position requires mitigating the risk of falling. A high standing function indicates good balance and low falling risk.

We describe the VLTC. Jeka et al. reported a phenomenon called light touch contact (LTC), in which touching a fixed point of a light force reduces postural fluctuation [9]. Because physical contact is required for LTC, VLTC provides the effect of LTC virtually with no touch.

Figure 3 shows a simple system configuration. See [7], [8], and [9] for details. The system consists of a Wii balance board as a force plate for measuring the Center Of Pressure (COP), a web camera for photographing the subject during measurements, a vibrator attached to the subject's finger for VLTC, and a computer for controlling the system. The measurement is performed with the subject standing on the Wii balance board. The subject touches a virtual wall configured around the body. In the measurement, the subject is switched between a state in which the virtual reaction force is presented when touching the virtual wall and a state in which no virtual reaction force is presented. Evaluate the change caused by . The measurement time is 40 s.

First, the COP is calculated for the sagittal plane (X direction) and the coronal plane (Y direction) from the Wii balance board. The following eight indices are used to evaluate the support standing function: d_1: total trajectory length of COP (L_{COP}); d_2: rectangular area of COP (S_{rect}); d_3: outer peripheral area of COP (S_{peri}); d_4: average velocity of COP (v_{COP}); d_5: average vector of COP (L); and d_{6-8}: index variations associated with virtual partition state changes.

The standardized indices (I_l) are determined using the standard deviation (σ^l) and the mean (μ^l) of the standard subject data for each index value.

$$I_l = \frac{d_l - \mu^l}{\sigma^l} \quad (3)$$

Considering I_l allows the inconsistencies between the measured and controlled values to be assessed. Then, the weighted sum of I_l ($S(I) = \Sigma_{l=1}^{N+8} w_l I_l$) is calculated for comprehensive evaluation of the stationary functions. It is assumed that the relationship between age and standing function can be expressed as a non-linear function,

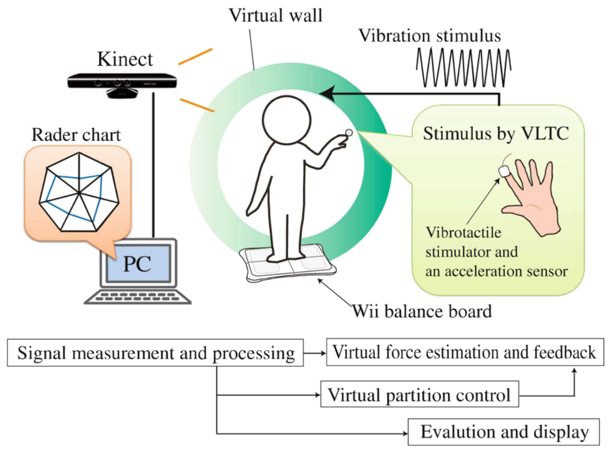

Figure 3. Overview of the Standing Function Evaluation System [7].

$$S_{age} = f_{age}(S(I)) \tag{4}$$

where $f_{age}(S(I))$ is a nonlinear function of the weighted sum, $S(I)$, for estimating the subject's age, and S_{age} is the subject's age estimated by the system, called "standing age" here. Similarly, it is assumed that the relationship between age and balance function can be expressed as a linear function in the current system as

$$B_{age} = g_{age}(I_1^{nc}) \tag{5}$$

where $g_{age}(I_1^{nc})$ is the total trajectory length of COP when VLTC is OFF, I_1^{nc} is used for estimating the subject's age , and B_{age} is the subject's other age estimated by the system, called "balance age" here.

Because standing age is calculated using several evaluation indices, it is an index of balance including the subject's sensory feedback. The smaller the standing age, the better the sense of balance. On the other hand, because the balance age is calculated from the index when VLTC is OFF, it indicates an individual's balance with no sensory factors. Therefore, the smaller the balance age, the better the potential balance.

V. EXPERIMENT FOR QUANTITATIVE AND SUBJECTIVE EVALUATION

A. Experimental Setup

The introductory tests were conducted on nine men and women aged 20s to 50s to verify the effects of assistance of the Smart Suit according to the schedules shown in Table I. The subjects are working at a distribution center, and is inspecting and loading on a truck. They are in the middle and lower back posture when carrying luggage and working on lanes. Table II shows the results of physical fitness tests as the physical abilities of each subject, and their working style.

First, a 1-day advance measurement was performed to determine the subject's physical ability and to explain the introductory test, including the physical fitness test, the standing function evaluation, the significance of the Smart Suit, and the instructions for its use. For 5 days in the following week, the subjects performed their usual work while completing the subjective working environment survey [10] without wearing

TABLE I. SCHEDULE FOR INTRODUCTORY TESTS FOR EVALUATING THE ASSISTIVE EFFECT OF THE SMART SUIT.

	the first week	the second week	the third week
Days	Five days Labor environment investigation	Five days Wearing period	Five days Introduction test period
Conduct contents	awareness examination usual work	usual work	awareness examination usual work
Smart Suit	non-wear	wear	wear

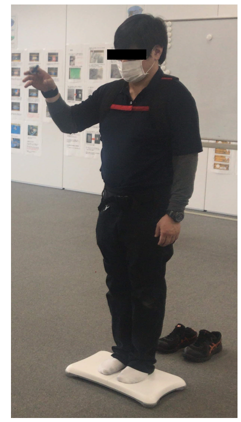

Figure 4. Measurements with the Standing Function Evaluation System wearing the Smart Suit.

a Smart Suit. In the next 5 days, they wore the Smart Suit, but they did not complete the subjective survey. In the subjective working environment survey, we conducted a questionnaire to ask about the languors of body and feelings at the start and end of work. The 5 days in the last week were the introductory test period, and the subjects did their usual work while wearing a Smart Suit and completed a subjective survey. After the introductory test period, a follow-up measurement similar to the pre-measurement was conducted and the subjects completed a feeling-of-use questionnaire for the Smart Suit. Figure 4 shows the advance measurement using the Standing Function Evaluation System with the Smart Suit.

The physical strength tests performed in the pre- and post-measurements were standing physical anteflexion, functional reach test, and grip strength measurement. These were measured twice each and the average value was used.

B. Experimental Results

1) Experimental Results of Subjective Evaluations: For the introductory test, we describe the results of the surveys of subjective experience and questionnaires for standing function evaluation and subjective evaluation. The results of the follow-up measurements were used. The results for the nine subjects are shown in Tables III and IV. The feeling of the assistive effect measured by the post hoc measurement questionnaire was evaluated by rating how much the assistive effect of the Smart Suit was felt on a 10-point scale. The response of subjects who could not determine whether there was an assistive effect was recorded as "none", that of the subjects who felt a subjective assistive effect from the Smart Suit was recoded as "yes", and that of the subjects who felt no assistive effect was recorded as "no". As shown in Table III, some subjects felt uncomfortable wearing at the time of walking or

TABLE II. PHYSICAL FITNESS TEST AND WORKING STYLE.

	Physical Fitness Test			Working Style	
NO.	Standing Position[cm]	FRT [cm]	Grasping Power[kgf]	Job Description	Working Road
a	7.0	41	46.0	Response to lane clogging	heigh
b	-7.5	37	50.5	Tractor docking	heigh
c	4.0	43	53.5	Loading and transporting luggage	heigh
d	11.0	46	25.0	Product inspection	low
e	-4.0	40	54.5	Refill items on the shelf	middle
f	1.5	50	48.0	Tractor docking	heigh
g	4.0	47	33.5	Store products on the shelf	low
h	-7.0	44	44.5	Sort the package	heigh
i	-3.5	41	34.5	Product inspection and sorting	middle

TABLE III. FEELING OF WEARING AND SUBJECTIVE EVALUATION.

	Profile		Feeling of wearing		Subjective evaluation	
NO.	Age [years]	Sex	At first	In the end	Feeling of Assistance Effect	Subjective Survey
a	46	male	Discomfort	Improved	8/10	none
b	33	male	Discomfort	Discomfort	6/10	No
c	53	male	Discomfort	Improved	8/10	none
d	38	female	Accustomed soon	No discomfort	2/10	Yes
e	42	male	Discomfort	Discomfort	7/10	Yes
f	55	male	Accustomed soon	No discomfort	8/10	none
g	28	female	Accustomed soon	No discomfort	1/10	Yes
h	56	male	Accustomed soon	No discomfort	8/10	Yes
i	52	male	Accustomed soon	No discomfort	7/10	none

at the beginning of use, but most subjects eventually became accustomed to using Smart Suit.

In the experience of the assistive effect in Table III, the two women may have felt the assistive effect less because their work did not involve much forward bending and their working roads are low as shown in Table II and III; thus, there was little opportunity to demonstrate the assistive effect of the suit. However, similar to subjective experiences of illness, the actual assistive effect does not necessarily agree with the feeling of the assistive effect. Thus, we identified subjects who did not feel the assistive effect, although there was an actual assistive effect .

Table IV shows the standing age and balance age measured using the Standing Function Evaluation System when the Smart Suit was not worn and when it was worn. The differences between the measurements show how much the standing function was improved by wearing the Smart Suit. In other words, the larger the difference between the measurements while not wearing the suit and wearing the suit, the larger the balance assistive effect. The effect was seen in six subjects; thus, several subjects benefitted from the Smart Suit.

2) Quantitative Evaluation Results.: The body sway measured in the Standing Position Function Evaluation System was analyzed. According to Yamamoto et al., body sway and low back pain risk are related [11]. People with lumbar lordosis had a large sway in the lateral direction (X direction), and those with a tendency to scoliosis or cervical tilt had a large sway in the anteroposterior direction (Y direction). Based on these observations, the risk of occurrence of lumbar pain could be reduced if the X direction and the Y direction of the center of gravity fluctuation are decreased when wearing the Smart Suit. Figures. 5 and 6 show the decrease in the effective value and speed of the body sway in each direction when the Smart Suit is worn. Six of the nine subjects showed a reduction in body sway in either the X or Y direction. We confirmed the

TABLE IV. STANDING AGE AND BALANCE AGE.

		Non-Wearing		Difference between wearing and non-wearing	
NO.	Age [years]	Standing Age	Balance Age	Standing Age	Balance Age
a	46	7	-15	-32	22
b	33	36	-30	7	5
c	53	55	36	10	9
d	38	33	6	12	13
e	42	38	-13	46	2
f	55	17	-15	16	5
g	28	32	-39	6	0
h	56	21	-21	19	-5
i	52	16	1	-6	-10

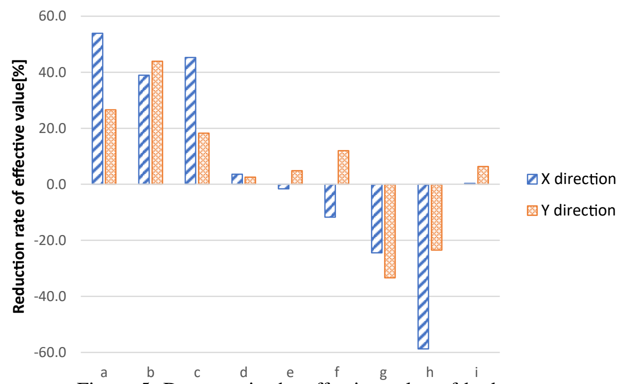

Figure 5. Decrease in the effective value of body sway.

correlation between the suppression of the body sway and the standing age and balance age that was used in the Standing Function Evaluation System (Table V). The difference in the balance age between wearing the suit and not wearing the suit and the suppression of body sway had coefficients of determination of 0.22 to 0.80. Therefore, by determining the difference in balance age, it is possible to determine whether the risk of lumbar pain is reduced.

The change in the sensory reweighting of the three sensory systems that contribute to standing in addition to the suppression of body sway is considered as the balance assistive effect of the Smart Suit. Sensory reweighting is a phenomenon in which a person adjusts the weighting of each sensory system when maintaining posture. Eikema et al. studied changes in posture and sensory reweighting when elderly people receive

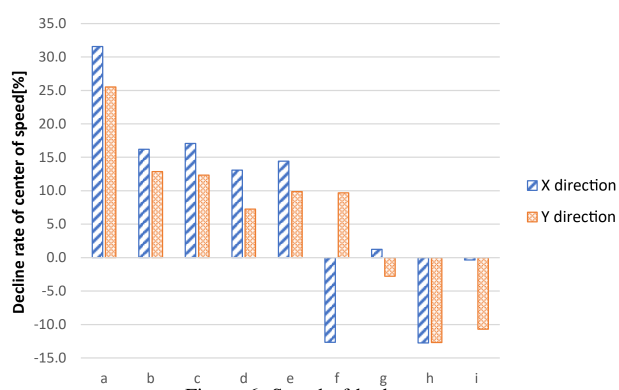

Figure 6. Speed of body sway.

TABLE V. COEFFICIENT OF DETERMINATION BETWEEN BODY SWAY AND THE STANDING FUNCTION EVALUATION SYSTEM.

	Difference of standing age		Difference of balance age	
	Effective value	Speed	Effective value	Speed
X direction	0.23	0.14	0.43	0.51
Y direction	0.08	0.07	0.22	0.8

sensory stimuli [12]. The balance assistive effect of the Smart Suit may affect the sensory system, similar to the VLTC of the Standing Function Evaluation System. We examined the effect of wearing a Smart Suit on the sensory system.

The evaluation method is as follows. First, wavelet transformation was performed on body sway measured by the Standing Position Function Evaluation System. The wavelet-transformed time series gain was divided by the frequency band of each sensory system. The frequency band was 0.02–0.3 Hz for vision, 0.3–1.0 Hz for vestibular + tactile sense, and 1.0–3.0 Hz for position sense. Then, the time average and the variance of the gain of each frequency band were calculated to evaluate quantitatively how much each sensory system contributed to posture maintenance. A large gain in a sensory system indicates that the system is preferentially used for balance in posture maintenance.

The VLTC used in the Standing Function Evaluation System decreased the gain of the vestibular + tactile and position sensory systems, indicating that these systems were replaced by the effect of VLTC. Therefore, when the Smart Suit caused a similar decrease in the gains of these systems, it indicated that the Smart Suit exerted a balance assistive effect on the sensory systems.

Figure 7 shows a box and whisker plot of the sum of vestibular + tactile and position sensory system gains after wavelet transformation of typical subjects h and i for when the Smart Suit was worn or not worn and VLTC was OFF or ON. For subject i, when the VLTC was OFF the gain was significantly reduced when the Smart Suit was worn, whereas there was no significant difference (confidence of 95% or more) for subject h. In addition, for subject i, when the Smart Suit was not worn, the gain was significantly reduced when the VLTC was ON, whereas for subject h, the gain was similar to when the VLTC is OFF. These results show that wearing the Smart Suit assisted subject i with similar sensory systems to the VLTC. Although the assistance of the sensory system by the VLTC was observed in one subject, the assistive effect of wearing the Smart Suit was confirmed in subjects a–e, g, and i. In addition, subjects b, d, and i showed reduced gains compared with the other subjects when the VLTC was ON and the Smart Suit was worn. Thus, the assistance from the VLTC and from the Smart Suit do not need to be simultaneous.

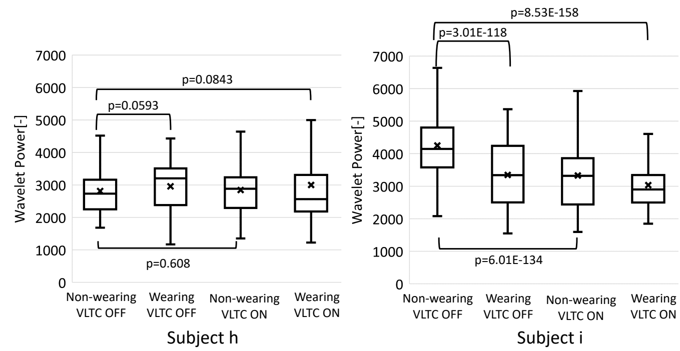

Figure 7. Sum of visual and vestibular + tactile gains for subjects h and i for when the Smart Suit is worn or not worn and VLTC is OFF or ON.

VI. DISCUSSIONS

The balance assistive effect of the Smart Suit was evaluated by subjective evaluation, body sway, and sensory systems. There were some subjects who could not confirm whether they felt the assistive effect and some who thought that they did not feel the assistive effect. The presence or absence of the auxiliary effects did not necessarily coincide with these experiences.

Subjective evaluation showed that seven men felt the 10 levels of assistive effects. Among them, in the subjective survey, two of these subjects indicated they felt subjective assistive effects. In addition, the subjective survey results for the two female subjects who did not feel the assistive effects indicated that they did experience assistive effects . Therefore, simply examining the feeling of the assistive effect is insufficient for indicating the subjective assistive effect, and it is necessary to use a survey method, such as a subjective survey. In addition, all of the nine subjects reported a subjective Smart Suit assistive effect either by feeling the assistive effect or through their answers in the subjective survey.

Considering the suppression of body sway in the left and right direction and the front and back direction by the Smart Suit as an objective balance assistive effect, the assistive effect was recognized in subjects a–f. However, although subject b reported no assistive effect in the subjective survey, their body sway was suppressed by the suit. In contrast, subjects h and i did not have their body sway suppressed, but reported a subjective assistive effect in the subjective survey, and in particular, subject h evaluated the experience of the assistive effect as high. Therefore, the suppression effect of body sway does not necessarily coincide with the subjective evaluation.

The evaluation of the assistive effect of the Smart Suit on the sensory system was confirmed in seven subjects (subjects a–e, g, and i). Although subject h experienced an auxiliary effect subjectively, no objective suppression of body sway or auxiliary effect on the sensory system was observed. Although subject f experienced an assistive effect, the objective suppression effect of the center of gravity sway was recognized in only the front and back direction and no assistive effect on the sensory system was observed. The other seven subjects showed either an objective suppression effect on body sway or an auxiliary effect on the sensory system, and these auxiliary effects are factors in determining an auxiliary subjective effect.

Although the suppression of body sway and the auxiliary effect on the sensory system are factors that determine the subjective auxiliary effect of the Smart Suit, they are not the only factors. This may be because the balance assistive effect is evaluated in the standing posture and that the muscle assistive effect of the Smart Suit is not considered. The Smart Suit was designed to exert an assistive effect via the expansion and contraction of the elastic material in the forward bending posture; thus, the subjective evaluation may be determined by the assistive effect for forward bending. Depending on the subject, the muscle strength assistive effect may also have a large effect on subjective evaluation.

We confirmed that a balance assistive effect was exhibited even when standing. The results suggested that the assistive effect might not only suppress the center of gravity sway, but also have an assistive effect similar to LTC on the sensory system. The subjective assistive effect, suppression of body sway, and assistive effect on the sensory system measured in this research are factors in judging whether the Smart Suit will have an assistive effect. Therefore, our results will allow quantitative evaluation of the balance assistive effect of the Smart Suit by suppressing body sway and assisting the sensory system.

VII. Conclusion and Future Works

In this paper, we evaluated the balance assistive effect of the Smart Suit subjectively and objectively. Subjective assistive effects were evaluated by the feeling of assistive effects and subjective experience. In the interviews, seven men out of nine subjects felt the assistive effect. On the other hand, according to the subjective survey, four subjects experienced the assistive effect, and these results were not necessarily consistent. Therefore, investigating subjective experience showed that there were subjects who needed the assistive effect even though they did not feel the assistive effect. The suppression of the body sway was evaluated by the effective value of the body sway in the lateral direction (X direction) and the longitudinal direction (Y direction) and the speed of the sway. Wearing the Smart Suit suppressed the body sway in six subjects, and the suppression was correlated with the difference between the balance ages measured by the Standing Function Evaluation System while not wearing and wearing the Smart Suit. Therefore, we showed that the body sway suppression effect can be measured quantitatively by using the Standing Function Evaluation System. In addition, by looking at the change in frequency gain of each sensory system in a Smart Suit based on the sensory reweighting model, we verified the auxiliary effect on the sensory systems using wavelet transform. A decrease in the frequency gain of the vision and vestibular + tactile systems was observed in seven subjects. We confirmed that the Smart Suit has an assistive effect on the sensory system similar to LTC. However, these evaluations of the relationship between the subjective and objective assistive effects did not necessarily agree. Although the suppression of body sway and the auxiliary effect on the sensory system were recognized as objective auxiliary effects, they could not explain the subjective auxiliary effect; however, they are probably important elements.

In future, we intend to examine not only the standing posture, but also the assistive effects in a forward bending posture that the Smart Suit was designed to exert. In addition to balance assistive effects, we also want to evaluate the muscle assistive effects and the physical abilities of the subjects. It is necessary to investigate how much these other effects affect the subjective auxiliary effect. Our goal is to establish a method to assess these effects comprehensively and conduct quantitative screening to see if a person can benefit from the Smart Suit.

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