A Model of Burden Sense from Psychophysical Factors in Lifting Action with and without Power Assist Device

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***Abstract*—In light of Japan's low birthrate and aging population, technology is needed for facilitating the activities of elderly persons as well as their caregivers. Wearable assist devices, such as the Smart Suit Lite (SSL) developed at our laboratory, are effective for this purpose. It is important to evaluate such devices from not only physical, but also from psychophysical perspectives. Experiments involving lifting a heavy object with and without SSL were conducted, and SSL was evaluated psychophysically. The muscle activity was measured by surface electromyography. The psychophysiological evaluation was conducted by using the visual analogue scale, in which reductions in load of 22.01% for muscles and 19.74% for the sense of lumbar load were confirmed. This report proposes the human load sense model based on the sense of weight and the amount of muscular activation. This model is expected to find application in humanoid robots for robust evaluation of power assist devices.**

Keywords-Human Sense Model; Burden Model; Power Assist; EMG.

I. INTRODUCTION

Support technology that facilitates daily operations is necessary for Japan's aging society. In addition to activities associated with caregiving and agricultural work, lifting of heavy objects in everyday activities undoubtedly applies a heavy burden on the low back[1][2].

At present, many researchers are focusing on power assist devices that can amplify muscle force or support movements. Among these, wearable power assist devices are attracting particular attention. Such wearable power assist devices can be categorized into active power assist devices with drives, such as Hybrid Assistive Limb (HAL) by Sankai[3] and a muscle suit by Kobayashi[4], and passive power assist devices, such as a suit-type back muscle supporter by Yamazaki[5] and an assist suit by Maeda[6]. Generally, active power assist devices with large force output necessary for several-fold amplification of forces applied by the wearer require power sources and many actuators, which makes them extremely heavy. In contrast, the main purpose of passive power assist devices without power sources is the reduction of the physical burden on the wearer rather than force amplification.

Figure 1. Smart Suit Lite

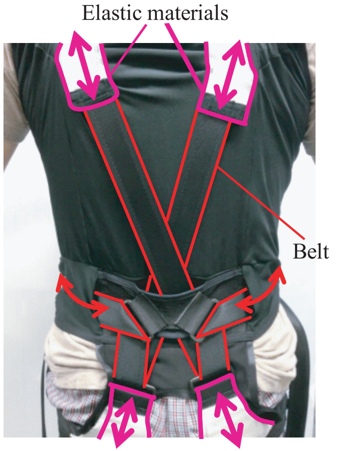


Figure 2. Appearance of elastic materials

We are developing a passive power assist supporter named "Smart Suit Lite (SSL)[7]" shown in Figure 1 for the purpose of preventing lumbar injuries. SSL is an assistive power suit made of elastic materials (rubber belts). It uses elastomeric forces generated when wearers change their posture to reduce burden in the lumbar region. The appearance of the elastic materials is shown at Figure 2.

The evaluation of such support devices is as important as their actual development. Related works evaluated the assist technology only physically. However this study evaluated SSL not only physically but also psychologically. It is important to evaluate from the both sides of the psychological and physical because these technologies are used by human. Inoue develops evaluation method based on physical and psychological burden in care[8]. In fact, evaluation by humans it is important to evaluate from the both sides of the psychological and physical. In this regard, SSL has been evaluated physically by humans[7]. Although its power assistance effect has been confirmed, its effect on the senses of the wearer should also be evaluated. Inspection of the psychophysical effect of such devices by humans is associated with difficulties in considering individual differences and the condition of the wearer on the day of the experiment. This is a disadvantage in comparison with related study evaluating only physically.

In a recent study, wearable assist devices were evaluated by humanoid robots[9]. In this approach, if the motor torque of the humanoid robot is assumed to be the same as the average torque of a human limb joint, the burden on a human limb joint can be estimated virtually by the value of motor torque of the humanoid robot. Humanoid robots thus make it possible to perform evaluations that are not influenced by individual differences and conditions. However, it is difficult for humanoid robots to evaluate the sense of burden. Thus, we considered that humans evaluate the sense of burden from some information, for example, the weight of the lifted object, the amount of muscle force and the motion trajectory. In this way, it is possible for humanoid robots to evaluate the sense of burden from equivalent values.

In this study, we inspected the physical and psychophysiological effects of wearing SSL and evaluated the human burden sense model in lifting a heavy object from the sense of weight and the amount of muscle force.

In this paper, first, we proposed the Human burden sense model. Next, The experiment of lifting with/without SSL was explained and the results were shown psychophysically. Finally, we considered the the Human burden sense model.

II. HUMAN BURDEN SENSE MODEL

In this section, we suggest the human burden sense (HBS) model based on four following hypotheses.

- Hypothesis 1:
  First, we suppose that the HBS is expressed to the sense of weight and the amount of muscular activation. We consider that the sense of weight might not be constant for a given object weight in the lifting. The cases of lifting the same weight many times and becoming used to the weight, and the case of lifting a weight without prior weight lifting experience or information about the weight are different from the perspective of the sense of weight [10]. Therefore, using the sense of weight as a constitution parameter of the HBS model is suggested. In addition, we consider that the burden sense changes by the quantity of muscular strength.
- Hypothesis 2:
  We suppose that the HBS is proportional to the sense of weight and the amount of muscular activation, and expressed by those linear combination. We defined sense of weight as S_w, sense of lumbar burden as S_{lb}, muscular activity as E_l. The formula of the HBS model is

$$S_{lb} = \alpha S_w + \beta E_l + L_0 \qquad (1)$$

- Hypothesis 3:
  The coefficient α denotes the sensitivity with respect to the sense of weight, and the coefficient β denotes the sensitivity with respect to the amount of muscular activation. Even though S_w has 0, muscular activity is needed for lifting and S_{lb} has a minute value. The constant term L_0 is the adjustment term for it. We hypothesized that the sense of weight does not change when wearing SSL, and a person wearing SSL has the same sense of weight as when not wearing SSL. In addition, we hypothesized that the sense of lumbar burden in lifting with SSL is the same in value as lifting without SSL when the sense of weight and the amount of muscular activation have the same values as in the case of lifting without SSL. In other words, α, β and L_0 is formed independent of whether SSL is worn.
- Hypothesis 4:
  The sense of lumbar burden is considered to increase together with the increase in intensity of the sense of weight and the amount of muscular activation. Therefore, in the ideal model, α and β are as follows:

$$\alpha > 0, \beta > 0 \qquad (2)$$

Therefore we consider that the HBS model is expressed by formula(1) and satisfied formula(2). A value of E_l becomes small by wearing SSL, and the value of S_{lb} becomes small with it.

III. LIFTING WITH/WITHOUT SSL

We measured the amount of muscular activation to quantify the effects of SSL in terms of reduction in burden and the intensity of the sense of burden in lifting a heavy box. The subjects were 5 healthy men without past or present clinical history of musculoskeletal system injury. The number of subjects is small because it was a purpose to look at the validity of the experiment technique and the tendency of the model that hypothesized. Information about each subject is given in TABLE I. The details of the experiment were explained in advance to the subjects, and their consent to participate was obtained.

There are two main lifting movements. The first involves squatting, in which the knees are bent and subsequently extended as the person lifts the object. The second involves

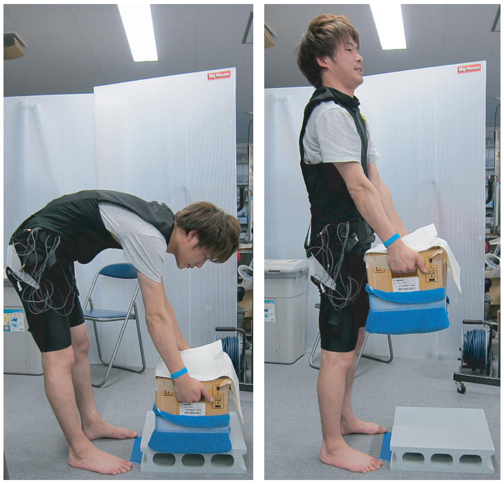


Figure 3. Lifting motion

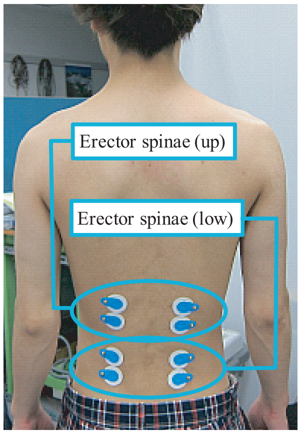


Figure 4. Sites measured by electromyography

stooping, in which the knees remain extended and the back is bent instead.

In this experiment, subjects were instructed to lift a heavy object from the stooping posture (Figure 3). Fujimura has reported that the maximal voluntary contraction (%MVC) of erector spinae in the stooping posture is larger than in the squatting posture in the lifting action[11]. The aim of this research was to examine the effect of wearing SSL on the low back; for this reason, we adopted the stooping posture for evaluating the burden on the erector spinae.

The center of gravity of a box (40 (W) × 25 (D) × 28 (H) cm) was situated at its geometrical center, and the handle of a heavy object was placed at a height of 32 cm above the ground. The subjects stood in front of the object, with their feet positioned such that the distance between them was the same as the distance between the shoulders. The weight of the box was changed in units of 5 kg between 15 and 25 kg,. The box was covered in order to prevent the subjects from estimating its weight from its contents (Figure 3).

The motion period of 8 s was controlled with a metronome. Each subject lifted each weight 4 times (for a total of 12 lifting motions) in random order. The experiment was conducted on 2 different days, where subjects lifted the box with SSL on one day and without SSL on the other. The second dynamic lifting session was conducted at least 2 days after the first session to allow for fatigue recovery.

TABLE I. SUBJECT DATA

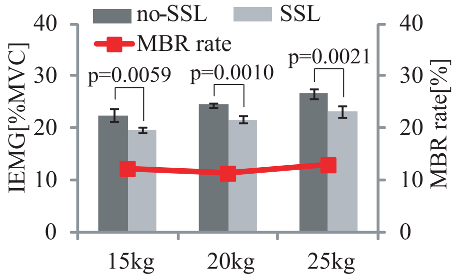
Subject	Age	Height[cm]	Weight[kg]
A	23	181	78
B	25	165	57
C	23	166	58
D	22	172	60
E	23	164	62
Average	23.2	169.6	63.0
SD	1.10	7.09	8.60

The muscular electric potential at the erector spinae muscles was measured with a data logger (DL2000; S&ME Inc.) with a sampling period of 1 millisecond. The measuring sites are shown in Figure 4. The skin was prepared at each site by abrading the area with tissues soaked in alcohol. We measured the muscular activation from the time to start bending towards for lifting to the time to be in an upright stance after putting the object. In this research, average rectified values (ARVs) obtained by integrating by unit time the rectified waveforms in the electromyograms were taken as the amounts of muscular activation. ARVs were normalized by the 100%MVC method, in which the amount of muscular activation in certain aspects of the movement are represented by their ratios to the amount of muscular activation at MVC. Given that MVC represents in its own terms voluntary and static conditions, muscular activation during movements may sometimes exceed that at 100%MVC[12][13]. To calculate %MVC, the muscle action potential at the time of maximum voluntary contraction at erector spinae was measured for 5 s.

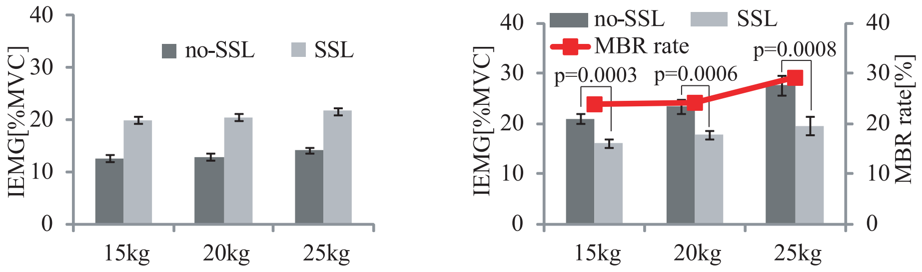
In terms of burden intensity, the sense of weight and the sense of lumbar burden were measured with the visual analogue scale (VAS) [14]. VAS is a simple and frequently used method for assessing variations in pain intensity. In clinical practice, the percentage of pain relief, assessed by VAS, is often considered as a measure of the efficacy of treatment. VAS is used widely as a tool for subjective evaluation and is not limited to the evaluation of pain. VAS is a line 10 cm in length with “no pain” at the left end and “worst pain imaginable” at the right end, and the subjects were instructed to rate the level of pain that they were currently experiencing. The intensity was measured for 4 subjects (A to D).

IV. MUSCLE BURDEN ASSISTANCE EFFECT

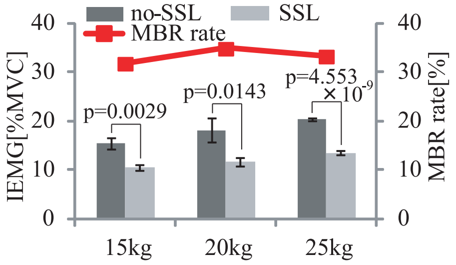
Figure 5 shows the average amount of muscular activation [%MVC] in lifting movement at the upper parts of erector spinae according to the lifted weight. The muscle burden assistance effect was evaluated by the total amount of muscular activation [%MVC] in the lifting movement. The amount of



(a) Subject A (b) Subject B



(c) Subject C (d) Subject D



(e) Subject E

Figure 5. IEMG of erector spinae (upper part)

muscular activation in all subjects increased depending on the weight of the object.

In 4 of 5 subjects, the amount of muscular activation in the case of wearing SSL was lower than that in the case of not wearing SSL (no-SSL). Such effect was not seen in subject C. As described below, the amount of muscular activation decreased in the lower erector spinae for subject C. We consider that subject C changed the lifting motion because of SSL, and therefore the muscles used for lifting changed.

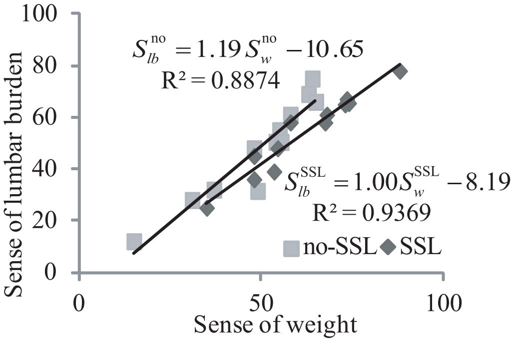
The muscular burden reduction (MBR) rate η was defined using the following equation for the evaluation function of the assistive effect.

$$\eta = \left(1 - \frac{\int_0^T V_{\mathrm{EMG}}dt}{\int_0^T V_{\mathrm{EMG0}}dt}\right) \times 100 \qquad (3)$$

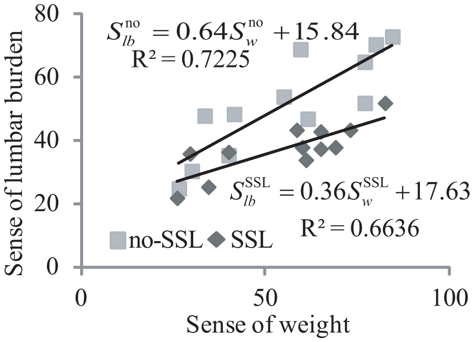
V_{EMG0} denotes the normal amount of muscular activation and V_{EMG} denotes the amount of muscular activation with assistive power provided by SSL, both of which are integrated by the motion period T. This represents the rate of reduction in the amount of muscular activation due to assistive power from SSL. In the 4 subjects whose respective amounts of muscular activation decreased. The analysis was performed t-test and each p-value was shown in Figure 5(a), 5(b), 5(d), and 5(e). Except only one result, p-values were lower than 0.01. Therefore significant difference was shown.

TABLE II. MBR RATE

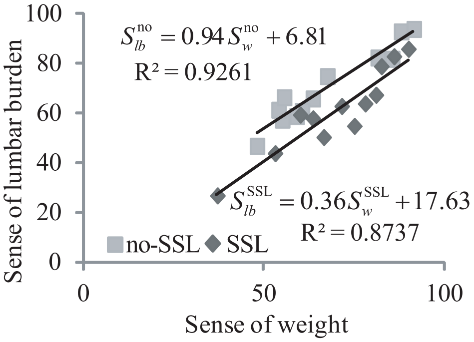
Subject	η[%]
A	12.16
B	16.78
D	25.73
E	33.37
Average	22.01



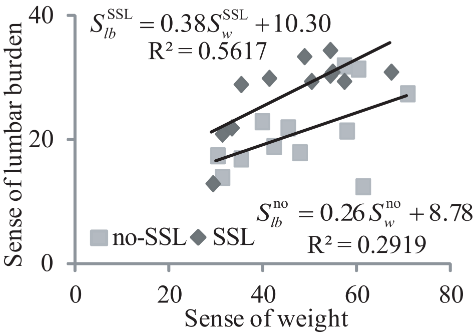
(a) Subject A



(b) Subject B



(c) Subject C



(d) Subject D

Figure 6. Sense of weight and sense of lumbar burden

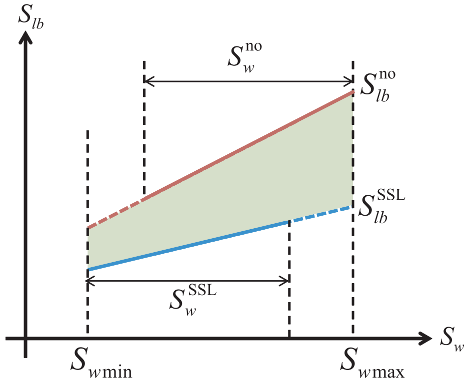


Figure 7. Interval of integration for calculating the MBR rate

TABLE III. SBR RATE

Subject	ς[%]
A	13.92
B	27.10
C	18.21
D	(-34.45)
Average	19.74

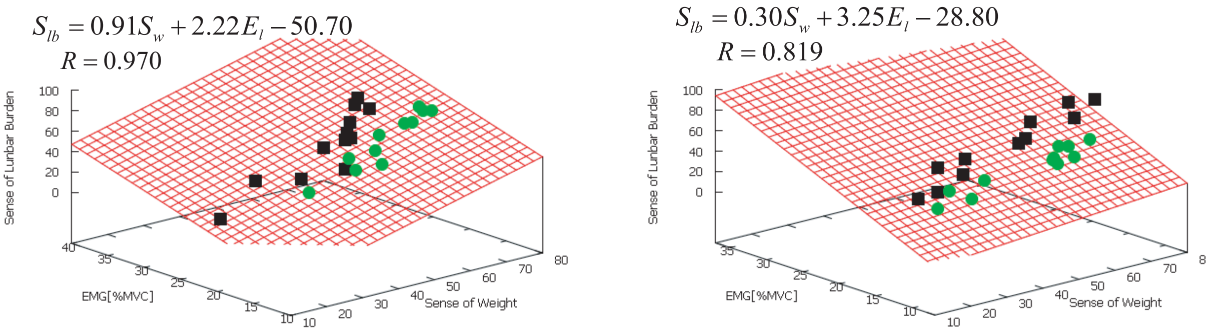
The MBR rates were calculated by fomula(3) according to the weight of object and shown as line graphs in Figure 5(a), 5(b), 5(d), and 5(e).

There was no correlation between the change in MBR rate and the lifted weight in the case of 4 subjects. Thus, we calculated the MBR rates for those 4 subjects by disregarding the lifted weight. The results are shown in TABLE II. According to the results, the average assistance rate at the erector spinae muscles in 4 subjects was 22.01%, and the amounts of activation of the erector spinae muscles subject to assistive power by SSL decreased accordingly.

V. SENSE OF LUMBAR BURDEN ASSISTANCE EFFECT

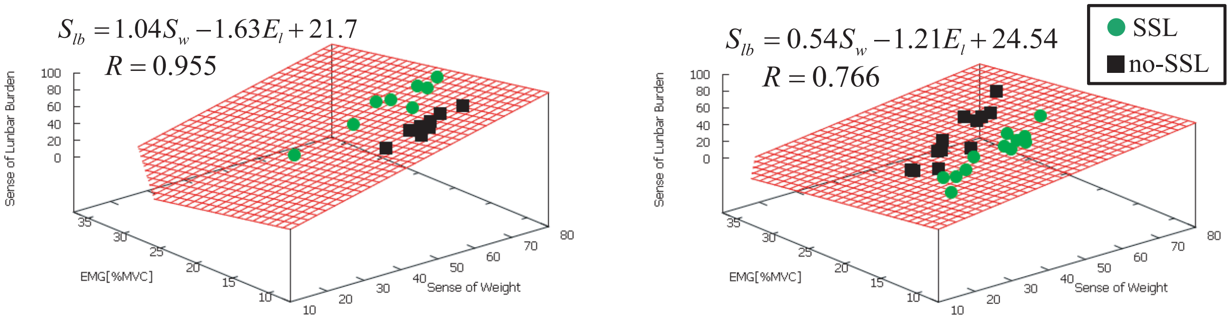
We measured the intensity of burden as the distance from the left edge in VAS to the line indicated by the subjects. The subjects were instructed to use VAS to score their evaluation of the burden on the low back as well as the entire body. At the same time, the subjects were also instructed to use VAS to estimate the weight of the object they lifted. An evaluation of the sense of lumbar burden was performed in terms of the relationship between lifting with SSL (With SSL) and without SSL (no-SSL). The relationship between sense of weight and sense of lumbar burden is shown in Figure 6. The horizontal axis denotes the sense of weight, and the vertical axis shows the sense of lumbar burden.

The relationship is derived from a regression formula that approximates the relationship between the two parameters by the least squares method depending on whether SSL is worn. S_w^{SSL} was bounded by S_w when the subject performed lifting with SSL, and S_w^{no} was bounded by S_w when the subject performed lifting without SSL. When we considered the range $S_{w\max}$ to $S_{w\min}$ (Figure 7), $S_w \leftarrow S_w^{\mathrm{SSL}} \cup S_w^{\mathrm{no}}$,



(a) Subject A

(b) Subject B



(c) Subject C

(d) Subject D

Figure 8. Burden sense model

S_{lb}^{SSL} show small values compared to S_{lb}^{no} in 3 of 4 subjects. From this result, it can be concluded that subjects felt a burden reduction effect by wearing SSL. We defined the sense burden reduction (SBR) rate ς as in formula (4) and calculated it for these 3 subjects.

$$\varsigma = \left(1 - \frac{\int_{S_{w\min}}^{S_{w\max}} S_{lb}^{\mathrm{SSL}}(S_w)dS_w}{\int_{S_{w\min}}^{S_{w\max}} S_{lb}^{\mathrm{no}}(S_w)dS_w}\right) \times 100 \qquad (4)$$

The results are shown in TABLE III. The average of ς for 3 subjects was 19.74%. Therefore, SSL could have the effect of reducing the sense of lumbar burden, similarly to the case of muscles.

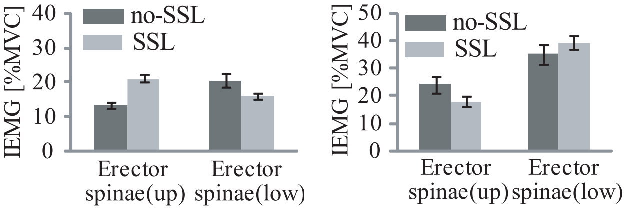
VI. RESULT OF HUMAN BURDEN SENSE MODEL

We inspected an effect of SSL from both physical and psychophysical points of view in Sections IV and V. We combine these perspectives in this section and consider the human burden sense (HBS) model from a psychophysical perspective. The results indicated that the amount of muscular activation decreased, and that the sense of lumbar burden decreased substantially through the use of SSL. The feeling of reduced burden due to the decreased amount of muscular activation is natural. Therefore, we concluded that the sense of burden in lifting depended on the amount of muscular activation and the weight of the lifted object.

We modeled HBS of each subject by formula(1) based on the least squares method using the sense of weight and the amounts of muscular activation not depending on whether SSL is worn. The results are shown in Figure 8 as aspect graphs. The multiple correlation coefficient is larger than 0.7 for all subjects. This value is sufficient for explaining the HBS from the sense of weight and the amount of muscular activation.

As a result, 2 of 4 subjects (A and B) satisfied the condition of the ideal model (formula(2)). We discuss the results for these 2 subjects who did not satisfy the conditions of the ideal model.

i) Subject C : We failed to obtain an ideal model for this subject, where β had a negative value. The sense of lumbar burden for subject C decreased when SSL was worn (Figure 6(c)). However, the amount of muscular activation of subject C increased in the upper parts and decreased in the lower parts of erector spinae (Figure 9(a)). The reason for this result was considered to be the change in the way muscles



(a) subject C (b) subject D

Figure 9. IEMG of erector spinae (upper and lower parts)

are used when wearing SSL.

ii) Subject D: We failed to obtain an ideal model for subject D as well, where β had a negative value. The amount of muscular activation for subject D decreased in the upper parts and increased in the lower parts of erector spinae (Figure 9(b)). We considered that subject D felt a more intense sense of lumbar burden with SSL than without SSL because of the increased amount of muscular activation in the lower parts of the muscles.

VII. CONCLUSION

The effect of wearing SSL when lifting a heavy object was examined, whereby it provided assistance amounting to an average of 22.01% of the force effected at erector spinae muscles. In addition, a reduction of an average of 19.74% in terms of the sense of burden was confirmed by using VAS. The burden reduction effect has been confirmed from the points of view of both muscular activity and subjective evaluation. In addition, the human burden sense model was formulated by using the sense of weight and the amount of muscular activation [%MVC]. The sense of lumbar burden was consequently expressed by a single formula not depending on whether SSL was worn. Only two subjects satisfied this ideal model. The amount of muscular activation in humans is considered to correspond to motor torque of in robots, and the sense of weight in humans is considered to correspond to the output of distortion sensors attached to the end effectors of robots. These correspondences show the possibility of applying the human burden sense model to robots and realize the evaluation by robots. Therefore, this study leads to the realization of the robust evaluation for assist technology.

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