# Smart Suit® Lite: KEIROKA TechnologyPaper Title

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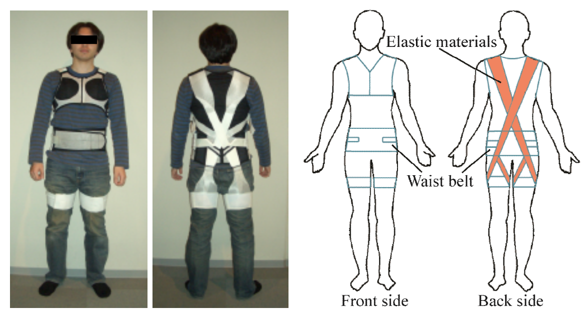
***Abstract*—We are developing a passive power assist supporter called Smart Suit Lite. Smart Suit Lite is a compact and lightweight power assist device that utilizes the elastic force of elastic belts. To design the Smart Suit Lite, we developed a motion-based assist method and an extended musculoskeletal model. The motion-based assist method was used to design the arrangements and properties of the elastic belts by utilizing the relation between the target motions and the corresponding muscle forces. To analyze the assistive forces provided by the elastic belts, skin segments that represent the surface of the human body features the extended musculoskeletal model and can reproduce changes in length of the body surface with changes in posture. In this study, we used the developed method to produce the Smart Suit Lite for care workers. Furthermore, through the "trial experiment" in this experiment, we found that wear comfort was strongly correlated with the assistance perceived by the user. Thus, we have improved the Smart Suit Lite from the aspect of wear comfort and verified the enhancement of the assistance provided by the device. In user testing, 90% of the participants reported a decrease in load on the low back during care work.***

***Keywords-Power Assist; Iomechanics; Human Body Dynamics Mode; KEIROKA Technology; Smart Suit Lite.***

## I. INTRODUCTION

In recent years, rapid aging of the population in many developed countries has led to increased demand for care workers. As a consequence, the physical burden placed on care workers by strenuous tasks and heavy workloads has become a severe problem. Minematsu [1] reported that half of care workers experience back problems. The main causes of low back pain, in particular, are overloading and bad posture [2]. In performing lifting tasks during routine duties, care workers tend to bend deeply at the waist, and the load on the low back is great [3]. Therefore, a power assist device for the low back muscles should be effective in not only reducing fatigue but also preventing lumbar disease.

Recently, many power assist devices have been developed. In particular, wearable assist systems have attracted considerable interest. Many of them are exoskeleton-type systems such as HAL [4], Muscle Suit [5] and BLEEX [6]. These exoskeleton suits are able to generate a large assistive force, but are weighty and large, owing to the necessity of both a power source and a number of actuators. On the other hand, some small and light-weight power suits have been developed, for example, Back Muscle Supporter [7], Simple Supporter [8] and Assist Suit [9]. Such devices utilize only passive force, and are designed to reduce the burden placed on the wearer.




(a) Smart Suit Lite (b)Form of Elastic belts

Figure 1: Prototype of Smart Suit Lite

In our laboratory, we have been developing a passive power assist supporter Smart Suit Lite (SSL) as one of KEIROKA assistive device. The device utilizes elastic force generated by elastic belts, and thus is safe, easy to use and suitable for nursing care applications. Because SSL does not have a control mechanism, the assistance provided by the system is determined in the design phase. Therefore, this study aims to design elastic belts and optimize the assistance provided for target motions.

Herein, we describe the design method of SSL, and report designs of elastic properties and arrangements of elastic belts for care work. Furthermore, trial experiments were conducted in a hospital and improvements based on the results are reported.

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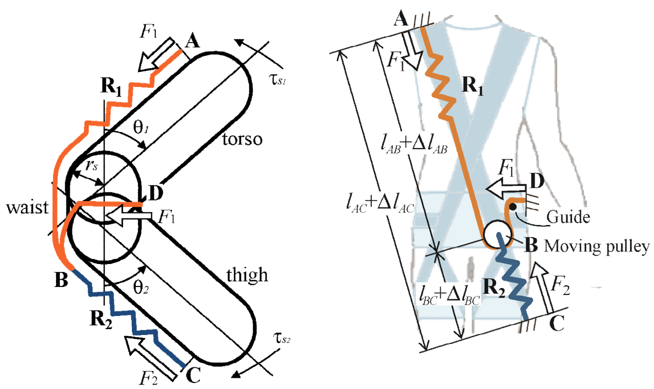


(a) Lateral view (b) Back view

Figure 2: Assist mechanism of Smart Suit Lite

## II. KEIROKA TECHNOLOGY

KEIROKA is a concept of assistive technologies. It does not only aim to reduce user's fatigue, but also achieve the following:

(1) secure assist for users and surroundings.

(2) sustainable assist to keep user's physical and mental performance.

(3) subliminal assist to keep user's natural motion. Smart suit is one of KEIROKA wearable assist devices designed by the above concepts. This paper describes the design methodology of smart suit lite for nursing workers and its results of field test.

## III. SMART SUIT LITE

Figure 1 shows a prototype of SSL. The elastic belts are arranged to connect the thighs and shoulders to the back, as shown in the figure. Furthermore, SSL is able to fit closely to the wearer's body and the assistive force is set according to the expected workload by adjusting the initial lengths of the elastic belts. Figure 2 shows a schematic side view of the device, and illustrates the assist mechanism in two dimensions; one of the elastic belts is shown. The elastic belt of the upper body $R_1$ and the elastic belt of the thigh $R_2$ are connected by a movable pulley at point $B$. In this configuration, we have belt of the thigh $R_2$ are connected by a movable pulley at point $B$. In this configuration, we have

$$F_1 = 2k\Delta l_{AB}, \quad (1)$$

$$F_2 = k\Delta l_{BC}. \quad (2)$$

Here, $\Delta l_{AB}$ is the change in length between $A$ and $B$; $\Delta l_{BC}$ is the change in length between $B$ and $C$; $F_1$ and $F_2$ are the elastic forces provided by $R_1$ and $R_2$, respectively; and $k$ is the spring constant.

If $2F_1 = F_2$ and $\Delta l_{AC} = \Delta l_{AB} + \Delta l_{BC}$ where $\Delta l_{AC}$ is the change in length between $A$ and $C$, then we have

$$\Delta l_{AB}:\Delta l_{BC} = 1:4. \quad (3)$$

Therefore, assistive torque $\tau_{s12}$ is

$$\tau_{s12} = \tau_{s1} + \tau_{s2} = \frac{6}{5} r_s k \Delta l_{AC}. \quad (4)$$

Here, $r_s$ is the moment arm of the elastic belts. Moreover, a part of the elastic force is used as a stabilization force, $F_t$, at point $D$. This stabilization forces act on the torso, in the similar manner as a corset.

$$F_t = F_1 = \frac{2}{5} k \Delta l_{AC}. \quad (5)$$

$\Delta l_{AC}$ increases as the wearer bends forward at the waist, and thus the assistive torque $\tau_{s12}$ is higher when adopting a posture that corresponds to higher load on the low back.

## IV. DESIGN OF ELASTIC BELTS USING MOTION-BASED-ASSIST METHOD

### A. Algorithm

The motion-based assist method is a design method based on models of the relation between the target motions and muscle forces. In this study, we design the elastic belts of SSL by using this method, which consists of the following steps.

Step1 Determine the sites and motions to be assisted.

Step2 Measure the target motions $\mathbf{M} = [\theta_1 \;\; \theta_2 \;\; \cdots \;\; \theta_N]$ in three dimensions with a motion capture system. Here, $N$ is the number of sampling points; $\theta_j$ is posture measured at time $j\Delta t$. ($\Delta t$ is the sampling period).

Step3 Calculate muscle forces $F_h$ in the target sites and moment arms $\mathbf{r}_h = \{r_{ij}\}$ for each degree of freedom by analyzing the motion $\mathbf{M}$ with a dynamic musculoskeletal model $\mathbf{G}_{SIMM}(\cdot)$. Then, calculate human joint torque $\tau_h$ from $F_h$ and $\mathbf{r}_h$.

$$[\mathbf{F}_h, \mathbf{r}_h] = \mathbf{G}_{SIMM}(\mathbf{M}), \quad (6)$$

$$\tau_h = \mathbf{r}_h \mathbf{F}_h. \quad (7)$$

(1)


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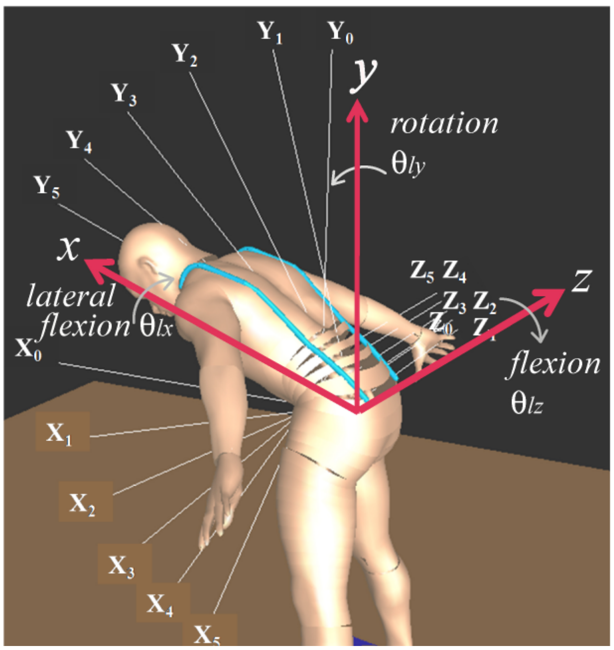
Step4 For arrangement $\mathbf{P}_s$ of the elastic belts, calculate the change in length of the elastic belts ($\Delta l$) and the moment arm of the elastic belts ($\mathbf{r}_s$) through analysis using a geometric skin segment model $\mathbf{G}_{SKIN}(\cdot,\cdot)$ and the motion $\mathbf{M}$.

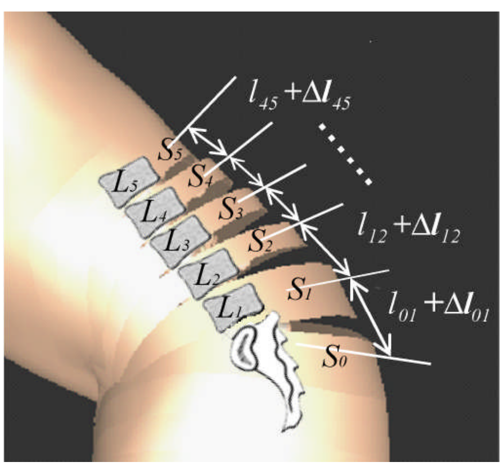
$$[\Delta l, \mathbf{r}_s] = \mathbf{G}_{SKIN}(\mathbf{M}, \mathbf{P}_s). \tag{8}$$

Step5 By repeating Step 4 for each arrangement, find the maximum assistive torque $\tau_s$, and determine the arrangement $\mathbf{P}$. Spring constant $k$ is assumed to be constant in this step.

$$\tau_s = \mathbf{r}_s k \Delta l. \tag{9}$$




(a) Skin segment and coordinate systems




(b) Lumbar segments in flexed posture

Figure 3: Skin segment model

(a) Changing patient's posture

(b) Helping patient sit up

(c) Changing patient's location

Figure 4: Caregiving movements to be assisted

Step6 Assuming that the assistance is provided by projection of the assistive torque $\tau_s$ to the human joint torque $\tau$ $h$, determine the desired elastic modulus $k$ from $\Delta l$ and $\mathbf{r}_s$, with desired assistive ratio $\hat{\eta}$.

$$k(j\Delta t) = \hat{\eta} \frac{|\tau_h(j\Delta t)|^2}{\Delta l(j\Delta t) \mathbf{r}_s(j\Delta t) \cdot \tau_h(j\Delta t)}, \quad (j = 1, \cdots, N). \tag{10}$$

Step7 Calculate the elastic property curve $\hat{k}(\Delta l)$ from elastic modulus $k$ and the change in length $\Delta l$ by fitting the data to following expression:

$$\hat{k}(\Delta l) = a_1 \Delta l^{a_2}, \tag{11}$$

where $a_1$ and $a_2$ are coefficients of the elastic property. In this manner, the arrangement and property of the elastic belts are designed.

## *B. Skin Segment Model*

To analyze the assistive force during motions, we developed a skin segment model that represents the body surface as shown in Fig.3 (a). We can calculate the changes in length of the elastic belts along the body surface by modeling the relation between posture and the shape of the body surface. To represent the elongation of skin covering the lumbar area, lumbar segments shown in Fig.3(b) are divided into segments $S_1 - S_5$, which correspond to the lumbar vertebrae ($L_1 - L_5$), and each segments is given coordinates $\Sigma_i (i = 1–5)$. In conjunction with lumbar angle $\theta_l$, which consists of flexion $\theta_{lz}$, lateral flexion $\theta_{lx}$ and rotation $\theta_{ly}$, skin segments move with respect to the pelvis at $\Sigma_0$ according to the following homogeneous transformation matrix.

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$$ {}^{i}\mathbf{T}_{i-1} = \begin{bmatrix} {}^{i}\mathbf{R}_{i-1}(\mathbf{C}_i\theta_l) & {}^{i}\mathbf{p}_{i-1} \\ \mathbf{0}^{\mathrm{T}} & 1 \end{bmatrix} \quad (12) $$

$$ {}^{i}\mathbf{R}_{i-1}(\mathbf{C}_i\theta_l) = \mathbf{R}_y(c_{iy}\theta_{ly})\mathbf{R}_x(c_{ix}\theta_{lx})\mathbf{R}_z(c_{iz}\theta_{lz}). \quad (13) $$

Here, $\mathbf{R}_x$ , $\mathbf{R}_y$ , and $\mathbf{R}_z$ are rotation matrices; $\mathbf{C}_i = \left[c_{ix}\ c_{iy}\ c_{iz}\right]^{\mathrm{T}}$ is a coefficient vector; and ${}^{i}\mathbf{p}_{i-1} = \left[p_{ix}\ p_{iy}\ p_{iz}\right]^{\mathrm{T}}$ is a translation vector. Then, there are gaps between segments as shown in Figure 3 (b). The change in length, $\Delta l$, of a path along the body surface is the sum of the change in length between each pair of adjacent segments (i.e., $\Delta l_{(i-1)i}$ $(i = 1...5)$).

$$ \Delta l = \sum_{i=1}^{5} \Delta l_{(i-1)i} \quad (14) $$

The size of the skin segments and transformation matrix can be adjusted with parameters, and thus a model can be prepared to suit the wearer.

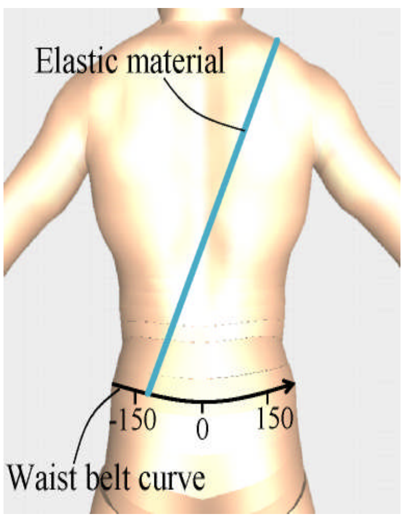
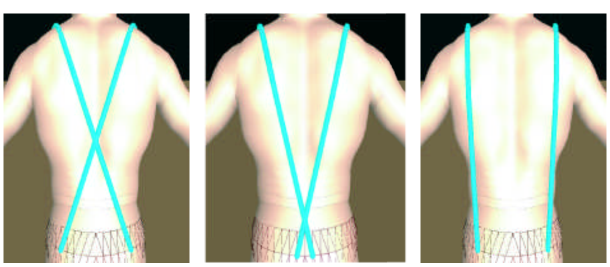



Figure 5: Waist belt curve and point of intersection



(a) $\mathbf{P}_0$ (b) $\mathbf{P}_4$ (c) $\mathbf{P}_{10}$

Figure 6: Arrangements of elastic belts

## V. Design of Smart Suit Lite for Care Work

### A. Target Motions for Assistance

In this study, common tasks performed around patient's (13) bed in care work were selected as the target motions. Figure 4 shows the selected motions. In preliminary experiment, these tasks were found to place a larger load on lumbar muscles compared with muscles in other regions. We took lumbar muscles to be the main assist target.

### B. Design of Elastic Belt Arrangement

In Steps 4 and 5 of the Motion-based assist method, we designed the arrangement of the elastic belts to provide effective assistance to lumbar muscles. Here, design parameters are via points $P_r$ and $P_l$ on the waist belt curve of the elastic belts (Figure. 5). Via points are symmetrically shifted from -150[mm] to 150[mm] in increments of 30[mm], such that 11 arrangement patterns are defined ($\mathbf{P}_j$ $(j = 0, \cdots, 10)$).

$$ P_{rj} = -P_{lj} = -150 + 30j \quad (j = 0, \cdots, 10). \quad (15) $$

Using these arrangements, we performed simulations of assistive torque during the motions of care work. First, motion capture and inverse dynamics analysis were carried out in Step 2 and 3 of the motion-based assist method. Table I shows the conditions of the motion capture experiment. Next, simulations of assistive torque were performed for $k = 500$[N/m]. Below, we define the torque assist ratio as a measure for evaluating the provided assistance.

$$ \eta_\tau = \frac{1}{T}\int_0^T \frac{\tau_s \cdot \tau_h}{|\tau_h|^2} dt. \quad (16) $$

Here, $\tau_s$ is assistive torque and $\tau_h$ is human joint torque.

Selected simulation results are shown in Figure 7. The highest assist rate was found in arrangement $\mathbf{P}_4$ (Figure 6). Thus, this arrangement of elastic belts was selected for further investigation.

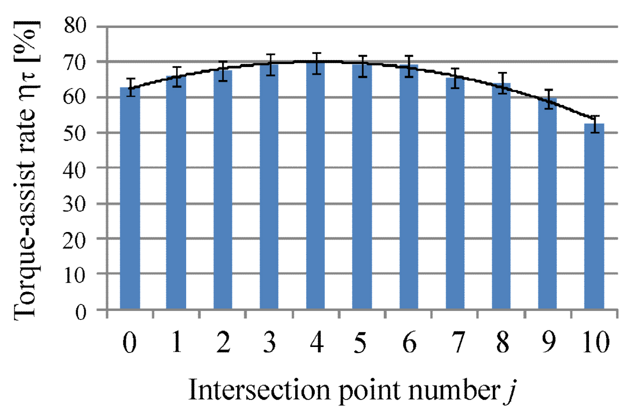



Figure 7: Simulation result for changing patient's posture

TABLE I. CONDITIONS OF MOTION MEASUREMENT

| | |
|---|---|
| Height of participant | 1723 mm |
| Height of bed | 400 mm |
| Height of patient | 1730 mm |
| Software | EvaRT4.3.57 |
| Cameras | 15 (HWAK-200RT) |
| Force plate | 2 (Kistler Inc.) |

## VI. TRIAL EXPERIMENT

### A. Experimental Conditions

To investigate the utility of SSL in the field, we performed a trial experiment at a hospital. Tables II and III show the details of the experiment. Participants wore SSL during working hours for five days and completed a questionnaire each day. Figure 8 shows a representative scene from the trial experiment.

Figure 8: Scene from the trial experiment

TABLE II EXPERIMENT CONDITIONS

| | |
|---|---|
| Period | July 5 - August 10, 2010 |
| Type of facility | Internal medicine and rehabilitation |
| Number of participants | 20 (caregiving staff members) |

TABLE III OVERVIEW OF PARTICIPANTS

| | | |
|---|---|---|
| Sex | Female | 19 |
| | Male | 1 |
| Age | 30–39 | 3 |
| | 40–49 | 6 |
| | 50–59 | 11 |
| Lumbar pain | Yes | 10 |
| | No | 10 |

### B. Results

#### 1. Feeling of fatigue

Participants evaluated fatigue before and after work on the Visual Analog Scale (VAS). The increases in fatigue due to work was compared between work done while wearing SSL and work done while not wearing SSL.

To do this, the increase in VAS for work with SSL was subtracted from the increase in VAS for work without SSL. Table IV shows the results. With respect to the mean (9) for all participants, there is no significant difference in the amount of change in VAS. Next, we divide the participants into groups by comfort while wearing SSL (comfortable, 7; uncomfortable, 13). For the group of participants who feel comfortable while wearing SSL, the amount of change in VAS is significantly lower.

#### 2. Load on low back during various tasks

In the questionnaire, the participants were asked whether SSL was effective for performing various tasks. Figure 9 shows the results. More than half of the participants in the comfortable group responded that SSL was effective for all the tasks. On the other hand, more than half of the participants in the uncomfortable group indicated that SSL was ineffective.

From these results, we can see that the subjective evaluation of the assistance provided by SSL depends on wear comfort. Causes of poor wear comfort include heat, tight fit and friction. By improving wear comfort, SSL can potentially receive better evaluations of its effectiveness in providing assistance.

TABLE IV MEAN VARIATION IN VAS

| | Wearing SSL | Without SSL | Difference |
|---|---|---|---|
| Total (n=20) | 30.1 | 29.5 | +0.6 |
| Uncomfortable (n=13) | 34.4 | 28.4 | +6.0 |
| Comfortable (n=7) | 22.1 | 31.5 | -9.4 |

## VII. SECOND TRIAL EXPERIMENT

### A. Improvement

In response to the first trial experiment, we improved SSL as follows ( Figure 10).

1. The neck hole was widened to avoid rubbing against the neck.
2. The vest was made larger to resolve a feeling of pressure.
3. A part of the vest was changed to a stretchable material to fit the wearer's body.

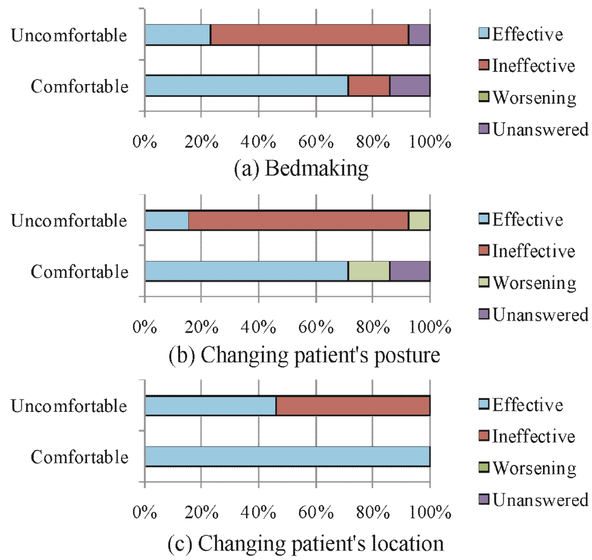



Figure 9: Subjective load reduction for various tasks

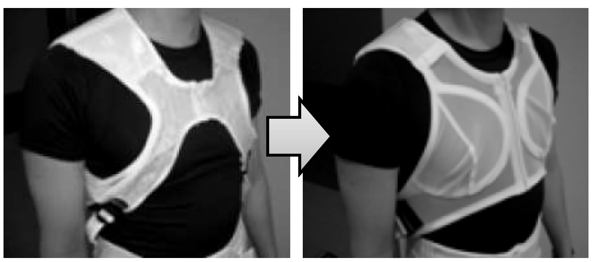


Figure 10: Improvement of Smart Suit Lite

### B. *Experimental Conditions*

To evaluate the effects of these improvements, we performed another trial experiment. Tables V and VI show the details of the experiment. Participants wore the old SSL and the improved SSL respectively, and evaluated fatigue due to work. In addition, because the assistive forces and mass of the improved SSL were almost the same as those of the old SSL, only the effects of wear comfort should reflect in the difference in the effectiveness of assistance.

### C. *Results*

1. *Wear comfort*

Figure 11 (a) shows results for evaluation of wear comfort at three levels ("good", "normal" and "poor"). The number participants who indicated that wear comfort was "poor" decreased 25 percentage points in comparison with the old SSL. Therefore, a notable improvement in the wear comfort of SSL was achieved.

2. *Lumbar load*

Participants evaluated the effectiveness of SSL in reducing the load on the low back on a six-point scale (0, "not at all effective"; 5, "very effective"). Figure 12 (b) shows the results. The mean score increased from 2.7 for the old SSL to 3.2 for the improved SSL. Therefore, SSL was notably improved in terms of the subjective reduction in load on the low back. In addition, participants evaluated fatigue on VAS as in the first trial experiment. The increase in average VAS value for work performed while wearing the old SSL was 16.4, whereas in the case of the improved SSL, this increase was 5.9; thus, for the improved SSL, suppression of the fatigue increase was 64.0% that for the old SSL.

The above results show that a significant improvement in the subjective effectiveness was achieved by improving the wear comfort of SSL. Therefore, the structure, materials and size variation of SSL should be further considered in the future.

TABLE V. EXPERIMENTAL CONDITIONS

| | |
|---|---|
| Period | December 13–24, 2010 |
| Type of facility | Internal medicine and rehabilitation |
| | (same hospital as first trial) |
| Number of participants | 20 (caregiving staff members) |

TABLE VI. OVERVIEW OF PARTICIPANTS

| | | |
|---|---|---|
| Sex | Female | 19 |
| | Male | 1 |
| Age | 20s | 1 |
| | 30–39 | 4 |
| | 40–49 | 2 |
| | 50–59 | 12 |
| | 60–69 | 1 |
| Lumbar pain | Yes | 7 |
| | No | 13 |

## VIII. CONCLUSION

In this paper, we introduced a design method of Smart Suit Lite using a motion-based assist method, and designed and evaluated Smart Suit Lite for care workers.

Aiming to achieve an assist ratio of 25%, we developed a skin segment model for analyzing the change in length of the surface of the human body, and designed the arrangement and properties of the elastic belts of SSL for care workers. In addition, we have manufactured Smart Suit Lite in accordance with the above mentioned designs for elasticity properties and arrangements, and we have verified its assistive effects through basic experiments. The results of the experiments show an average reduction of 24% in the amount of activation of the erector spinae muscle, proving the effectiveness of the power assistance device. Moreover, 20 care workers at a hospital wore SSL while performing their duties, and evaluated its effectiveness in providing assistance. Poor wear comfort was found to lead to low subjective effectiveness of assistance. Therefore, we modified the SSL with the aim of improving wear comfort. As a result, 90% of participants reported a reduction in load on the low back. The subjective feeling of fatigue was found to depend on various factors including comfort and habituation, and thus further long-term evaluations will be necessary in order for SSL to be used routinely.

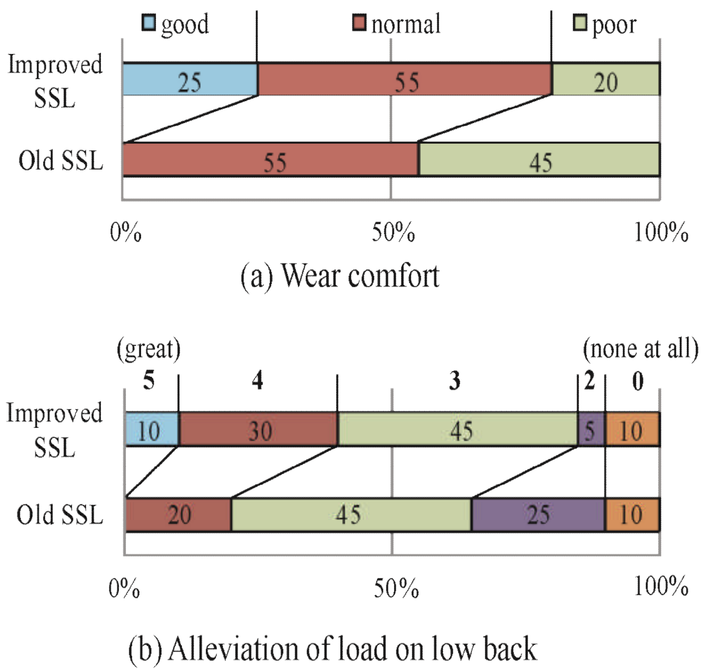



Figure 12: Evaluation

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