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Postural Stabilization by Trunk Tightening Force Generated by Passive Power-Assist Device*

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Abstract— **We are developing a passive power-assist supporter called *Smart Suit Lite*, which is a compact and lightweight power-assist device that utilizes the restoring force of elastic belts. Smart Suit Lite is designed not only to support muscles but also to stabilize the torso similarly to a corset. However, because a corset is always tight around the waist, negative effects caused by long-term use has been pointed out. In contrast, the tightening force generated by Smart Suit Lite increases only when the wearer adopts a posture corresponding to higher load on the low back. In this research, we performed two basic experiments to evaluate the static balance ability of wearers. As a result, the standard deviation of the lumbar angle decreased by 32.1% on average in wearers with low stability.**

I. INTRODUCTION

In Japan, which has a low birth rate and a rapidly aging population, the demand for caregiving work is rapidly increasing but care workers are in short supply because of their high turnover rate. A major reason for this high turnover is that caregiving work is hard work that imposes heavy physical burdens on care workers. In fact, half of all care workers are reported to complain of backaches [1].

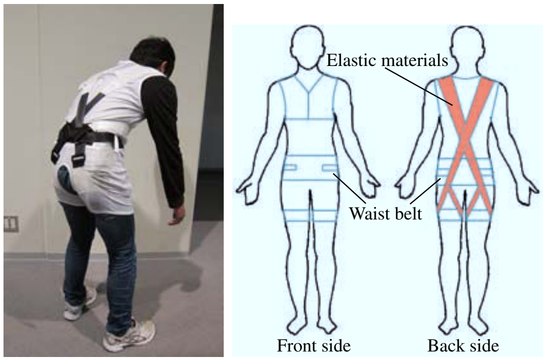
Movements encountered in caregiving include deeper forward flexion than in normal activities of daily living and lifting while in a twisted posture; such movements undoubtedly impose heavy loads on the low back. Thus, we can reasonably expect that reducing the physical burden will alleviate fatigue and prevent lumbar disorders.

To date, many studies have investigated power-assist devices for augmenting muscle forces and for supporting movement. In particular, wearable power-assist devices are attracting considerable attention in light of today's societal needs. Examples of wearable power-assist devices include active power-assist devices driven by motors, such as HAL by Sankai [2] and a muscle suit by Kobayashi [3]; and passive power-assist devices, such as Suit-type Back Muscle Supporter by Yamazaki [4], a simple supporter for reducing low back exertion by Imado [5], and an assist suit by Maeda [6]. These passive-type assistive braces support wearers without using actuators unlike the active-type devices. To prevent lumbar disorders in a more proactive manner, we are developing a passive power-assist supporter called "Smart Suit Lite" (Fig.1). The system is based on the concept of "KEIROKA", which aims to remove the load on the body and to reduce fatigue, rather than to amplify force. Smart Suit Lite is a compact and lightweight device made of elastic belts (rubber) that serve as an assistive power source; the system has high safety with respect to the surroundings. A portion of the elastomeric forces is utilized for muscle support and the remaining force acts as tightening force around the pelvis. Similarly to a corset, the system applies tightening force to the low back, serving to stabilize the trunk. This paper presents the results of experiments evaluating trunk stabilization by Smart Suit Lite during forward flexion. Changes in static postural stability are quantitatively evaluated through an experiment using Smart Suit Lite and an experiment using a waist belt that supplies only tightening force.

II. SMART SUIT LITE

A. Power-assist mechanism

This section describes the construction and power-assist principle of Smart Suit Lite. Fig. 1 shows a prototype of Smart Suit Lite, and Fig. 2 shows a schematic diagram of the assist mechanism. Smart Suit Lite has two elastic belts, but the belt on one side is only modeled since the belts are arranged symmetrically. Elastic belt $\mathbf{R}_1$ on the torso generates elastomeric force F_1 and is linked by a moving



(a) Prototype (b) Configuration of elastic belts

Fig. 1. Smart Suit Lite

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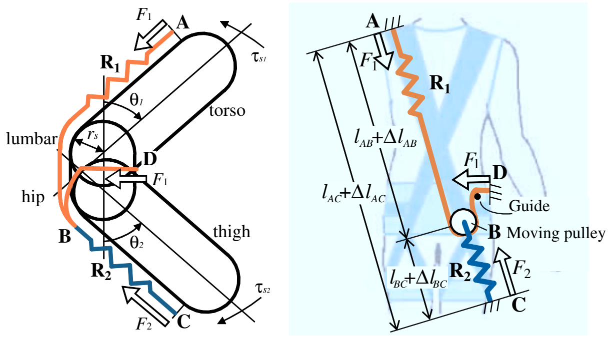


(a) Lateral view (b) Back view

Fig. 2. Assist mechanism of Smart Suit Lite

pulley to elastic belt $\mathbf{R}_2$ on the thigh, which generated elastomeric force F_2. The belts connect the shoulders and legs on the back. Elastic belt $\mathbf{R}_1$ is turned over at point B and connected to the waist belt at point D. Let Δl_{AC} denote the change in length between A and C when the wearer changes posture; Δl_{AB}, the change in length between A and B; and Δl_{BC}, the change in length between B and C.

The elongation of elastic belt $\mathbf{R}_1$ equals $2\Delta l_{AB}$ because $\mathbf{R}_1$ turns over at point B. The elastic belts generate the following elastomeric forces with elastic modulus k:

$$F_1 = 2k\Delta l_{AB} \tag{1}$$

$$F_2 = k\Delta l_{BC} \tag{2}$$

With $2F_1 = F_2$ and $\Delta l_{AC} = \Delta l_{AB} + \Delta l_{BC}$, the elongation ratio of the elastic belt between the torso and the thigh is expressed by $\Delta l_{AB} : \Delta l_{BC} = 1:4$. From these equations, assistive torque τ_{s12} for lumbar extension and hip extension is expressed as follows:

$$\tau_{s12} = \tau_{s1} + \tau_{s2} = \frac{2}{5} r_s k \Delta l_{AC} + \frac{4}{5} r_s k \Delta l_{AC} = \frac{6}{5} r_s k \Delta l_{AC} \tag{3}$$

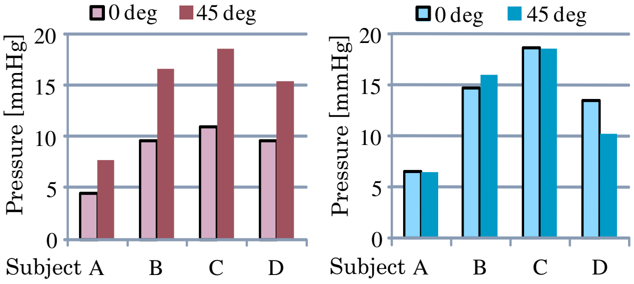
Here, r_s is the moment arm of the elastic belt at the lumbar joint. Moreover, the other elastomeric force F_1 acts on the waist belt to tighten it around the torso similarly to a corset.

$$F_1 = \frac{2}{5} k \Delta l_{AC} \tag{4}$$

Lumbar load increases with greater forward flexion at the waist [7]. Since elongation Δl_{AC} of the elastic belt increases as the wearer bends further at the waist, any postures imposing heavier loads generate greater τ_{s12} and F_1, that is, greater assistive effects.

The prototype of Smart Suit Lite for caregiving movements have been produced. We focused on muscle support effect, and designed the assistive torque to reduce 25% of back muscle activities during some care motions[8]. In this paper, this system is used to examine trunk stabilization.

Fig. 3. Sites where pressure on body was measured



(a) Smart Suit Lite (b) Corset

Fig. 4. Change in pressure on body versus posture

B. Tightening force generated by posture change

A lumbar corset is often used to prevent and treat low back pain. A corset limits movement in a specific direction and increases the intra-abdominal pressure to reduce the load on lumbar spine by applying pressure around it. It has been experimentally verified that a lumbar corset reduces trunk muscle activity and load during exertion. However, a drawback is muscle atrophy caused by excessive support of trunk muscles in long-term use [9]. Smart Suit Lite avoids this problem by supporting muscles only in a flexed posture and by not generating tightening force in an upright posture, as shown in the previous section.

Through experiment, the tightening force has been shown to change according to wearer's posture. Fig. 4 shows an example of those results. Four participants wore Smart Suit Lite or a corset, and pressure on the lumbar was measured by body pressure measuring device (Pressure scanning aid cero / CR-270; CAPE CO.,LTD.) when the lumbar flexion angle was 0 and 45 deg. The body pressures are evaluated by the average values of pressure applied to the iliac crest and the regio umbilicalis (Fig. 3). As a result, the pressure applied to the body showed almost no change between the flexed and upright postures when wearing the corset. In contrast, when wearing Smart Suit Lite, the pressure on the body in the flexed posture increased by 68.9% on average in comparison with an upright posture.

III. EXPERIMENTAL MEASUREMENT OF BALANCE ABILITY USING SMART SUIT LITE

We evaluated static balance ability to quantity effects of Smart Suit Lite on trunk stabilization during forward flexion.

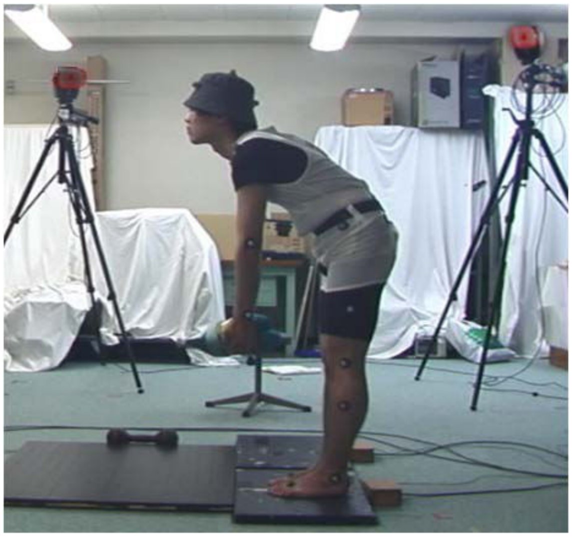


Fig. 5. Scene from the experiment

TABLE I
PARTICIPANTS IN EXPERIMENT

Participant	Age	Height [m]	Weight [kg]	Back strength [kg]
A	24	1.89	77.6	-
B	41	1.80	73.8	146
C	25	1.65	56.5	110
D	27	1.72	64.0	124
E	26	1.65	60.0	105

Participant A was excluded from back strength measurement because of a history of low back pain.

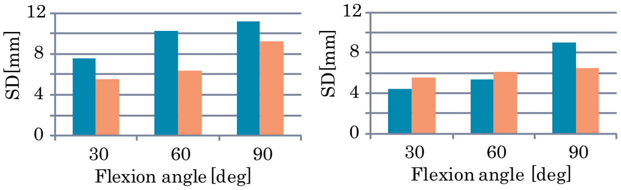
A. Methodology

The attributes of the five participants are given in Table I. In the experiment, a participant held 6 kg weight and maintained a flexed posture for 30 s, as shown in Fig. 5. The participant was instructed to stand with legs closed and to look at the fixation point located 3 meters ahead. Six experimental conditions were used (with and without Smart Suit Lite at lumbar flexion angles of 30, 60, and 90 deg), and each condition was measured three times in random order. Static balance ability was evaluated by measuring body sway with two floor reaction force gauges (9286A, Kistler Instruments) at a sampling frequency of 120 Hz. The signal was bandpass filtered from 0.02 to 10 Hz.

B. Results

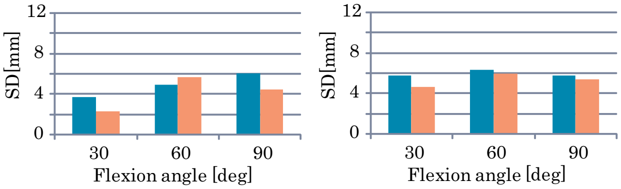
$\mathbf{P}(n\Delta t) = [P_x(n\Delta t),\ P_y(n\Delta t)]$ is the center of foot pressure (COP) measured at time $n\Delta t$. The x-axis is the lateral direction, the y-axis is the longitudinal direction, and origin is the 30 s average of COP $\left[\overline{P}_x,\ \overline{P}_y\right]$.

The standard deviation of COP is used to evaluate body sway. It is known that the standard deviation increases with decreasing postural stability. The standard deviation of COP along the y-axis is greater than that along the x-axis in all participants. This finding is attributed to the weight more easily inducing sway in the longitudinal direction. Therefore, we deal with only the results for the y-axis in this paper. Fig. 6 shows the results for each participant under each condition. It can be seen that the standard deviation is lower when wearing Smart Suit Lite in participant A at 30, 60, and 90 deg flexion, participant B at 90 deg flexion and participant E at 30 and 90 deg flexion.



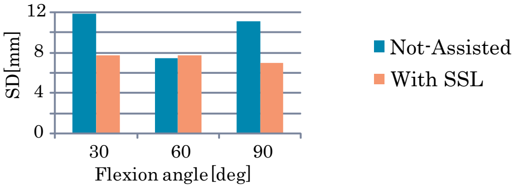
(a) Subject A

(b) Subject B



(c) Subject C

(d) Subject D



(e) Subject E

Fig. 6. Standard deviation of COP along y-axis

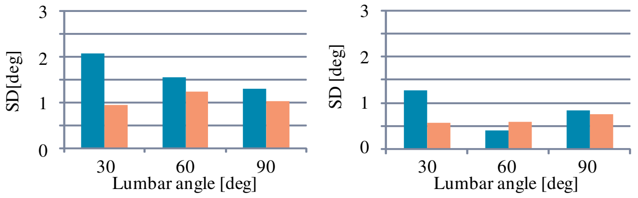
The figure shows that the participants whose sway was reduced had greater body sway without Smart Suit Lite than did the other participants. In addition, the posture in which sway was reduced had greater standard deviation without Smart Suit Lite. Such postures are thought to be difficult for the participant to stabilize. These results suggest that stabilizing effect of Smart Suit Lite is especially strong for wearers and postures with low stability. Body sway did not increase, even for participants and postures with high stability; therefore, Smart Suit Lite did not interfere with the movement for any participant.

IV. EXPERIMENTAL MEASUREMENT OF BALANCE ABILITY USING TIGHTENING FORCE

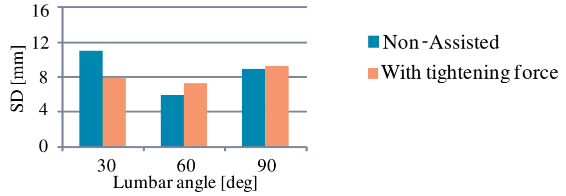
To verify in more detail the trunk-stabilizing effects of Smart Suit Lite, experiments examining balance ability were performed using a waist belt.

A. Methodology

The participant was participant A of the experiment described in the previous section. The stabilizing effect of Smart Suit Lite was strong in this participant. In this experiment, to measure the motion of the whole body, we used a motion capture system (Optical Motion Capture System EvaRT4.3.57; Motion Analysis Inc.) and six cameras (HWAK-200RT; Motion Analysis Inc.). To examine the

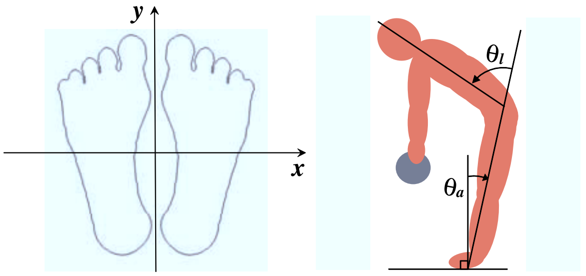


(a) Lumbar angle (b) Ankle angle



(c) COP (y-axis)

Fig. 7. Change in standard deviation



(a) COP (b) Joint angles

Fig. 8. Definition of coordinate system

effect of trunk tightening force alone, a waist belt was fixed around the trunk to apply a force similar to that applied by Smart Suit Lite. The participant held 6 kg weight and maintained a flexed posture for 30 s like the previous experiment. Six experimental conditions (with and without Smart Suit Lite at lumbar flexion angles of 30, 60, and 90 deg) were measured three times in random order.

B. *Results*

Fig. 7 shows the standard deviations of lumbar joint angle θ_l, ankle angle θ_a, and the y-axis component of the COP. Coordinate systems are defined as Fig. 8. The standard deviation of the lumbar angle was lower at all flexion angles, and on average, the standard deviation was reduced by 32.1%. Joint stiffness was increased by tightening around the pelvis, and the change in angle was decreased. The standard deviation of the ankle angle decreased at a lumbar angle of 30 deg and increased at a lumbar angle of 60 deg. Although the standard deviation of the ankle angle at 60 deg was initially small, lumbar sway was distributed as ankle sway by the tightening force. The correlation between the standard deviation of COP along the y-axis and the standard deviation of the ankle angle was 0.65; thus, the magnitude of body sway was correlated with the motion of the ankle joint. Therefore, waist load is possibly reduced by the trunk tightening force even if a significant effect does not appear in COP. Quantitative evaluation of this point is a task for future research.

V. CONCLUSIONS

The paper presented the results of evaluating the stabilizing effect of the passive power-assist supporter Smart Suit Lite. A brace that tightens around the pelvis like a corset increases abdominal pressure and stiffness of the lumbar spine. Stiffness along the long axis of the body increased, and the brace suppressed sway as a result. Since the tightening force of Smart Suit Lite increases as the wearer bends further at the waist, postures imposing heavier loads generate greater assistive effects. Therefore, we evaluated the change in postural stability due to wearing Smart Suit Lite when maintaining a flexed posture. The experimental results suggest that the stabilizing effect appears for wearers with low stability and does not interfere with the movement of wearers with high stability. More detailed analysis of the changes in joint stiffness and lumbar load will be a subject of future research.

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