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Paper:

Development and Evaluation of a Close-Fitting Assistive Suit for Back and Arm Muscle – e.z.UP®–

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This paper proposes a close-fitting assistive suit, called e.z.UP®, with a passive actuation mechanism composed of an adjustable structure. The suit can adequately assist the back and arm muscles of a user with the proposed layout of an arm assistive belt and a two-layer structure, respectively. With its lightweight characteristic (i.e., weighing 0.75 kg only), the proposed suit is portable and easy to wear without additional burden. By using the averaged Japanese body data, a simulation was conducted based on a human body model wearing our proposed suit to evaluate the layout of the arm assistive belt. The simulation results prove that the proposed suit can adequately assist the user's arm muscles based on the user's motion. An experiment involving the measurement of muscle activities is also implemented with seven young subjects and seven middle-aged subjects to evaluate the arm assistive belt and the two-layer structure. The experimental results reveal that the proposed suit can successfully and appropriately assist both the arm and back muscles simultaneously.

Keywords: manual handling workers, assistive suit, elastic materials, arm and back assistance

1. Introduction

Humans are still the main workforce in many occupations, such as those in the construction, agriculture, manufacturing, service, nursing care, and freight industries. Muscular injuries of manual handling workers, especially low back pain (LBP), can be caused by repeated motion and carrying heavy load in their daily tasks. LBP may influence the quality of life of workers significantly [1]. For employers, the financial loss may increase indirectly because of the lost productivity of workers who suffer from LBP. Montgomery et al. [2] determined that chronic LBP costs 1.2 trillion Japanese yen annually in lost productivity. Therefore, the designs of working strategies and physical support have been the focus of many studies. Wearable assistance devices/suits that can provide physical support with the active/passive actuation mechanism have been proposed [3–13]. Chen [14] revealed an indirect effect of LBP that occurs when a worker's arm muscle experiences localized fatigue because their lifting posture changes and increases the burden on the back muscles indirectly. The arm muscles are the weakest and become fatigued more rapidly relative to the larger muscle groups of the back and legs. Therefore, arm-muscle assistance is suggested to prevent injury to the lower back. Assistive devices/suits can be divided mainly into two categories according to the actuation mechanism: active and passive actuation mechanism.

Assistive devices with the active actuation mechanism use electric actuators (e.g., electric motor and artificial muscle) to provide assistive power [3–7, a–d]. Naruoka et al. [8] proposed a power-assist suit to prevent the burden on lower limbs of workers (e.g., care workers and logistics workers) by assisting the knee joint. However, in most devices with active actuation, a higher power output requires rigid frames, causing an increase in device weight. The weight must be carried by the user and can cause further burden on the lower limb. Additionally, the electric power source may restrict service lifetime and mobility. Therefore, devices/suits with passive actuation mechanism were developed in various studies and companies considering the weight in practical scenarios without an electric power source.

Due to the merits of being lightweight, having a compact size, and no electric power source, devices with the passive actuation mechanism, such as rubber and spring, have been proposed for manual handling workers. For upper-limb and arm assistance, the Working Power Suit [e] was introduced with an adjustable structure employing six 1-mm-thick stainless on the torso to assist the waist and detachable elastic belts to support the arm muscle. DAIYA Co., Ltd. introduced a product series named SHOKUNIN DARWING [f] for the assistance of the back and shoulder muscles.

For upper-limb assistance, in addition to using an elastic component, Nikkari Co., Ltd. proposed two types of arm-support devices [g] that weighed 1.8 kg and 2.7 kg to support agricultural and industrial workers and those who usually raise their arm to conduct daily tasks, respectively.

For waist assistance, Lotz et al. [9] developed an on-body personal lift assist device with rigid frame to support mainly the lower back during lifting task. The Laevo exoskeletons [h] supports the user's upper body to assist the back muscle further during bending or squatting. However, porters may require suits with soft, portable, and compact characteristics, especially when driving. Park et al. [10] proposed a soft wearable weight support device to support torque on the shoulder caused by the arm weight. Imamura et al. [11] proposed a passive power assist supporter, called "Smart Suit Lite," which focused on lower back assistance and torso stability. A product weighing 0.25 kg, named Rakunie [i], focused on lumbar support to reduce strain on the erector spinae muscle and biceps femoris (BFS) muscles by 17% on average. Support Jacket [j] utilized the proposed backbone along the caudal vertebra to the upper back by considering the spine curve to support the back. Apart from the Working Power Suit that can assist the waist and the upper limb muscles, Tanaka et al. [12] proposed a rubber suit consisting of rubber and nylon belts to assist both the arm and back muscles. Most passive actuation devices consider the assistance of both arm and back muscles separately. According to Chen's study [14], the prevention of arm-muscle fatigue is one of the key factors in preventing lower-back injury. Therefore, arm-muscle assistance must be considered a key factor to prevent lower-back injury.

2. Design of the Assistive Suit Prototype

Although the devices with active actuation mechanism can provide high assist power, the service time and the working environment may restrict their practical usability (e.g., temperature, humidity, etc.). The devices/suits with passive actuation may overcome this difficulty. In our previous paper, we proposed an assistive suit prototype consisting of rubber and nylon belts [12] for caregivers. The suit can assist not only the lower back but also the arm muscles. However, the unconcealable belt structure may cause hazards in daily tasks. To overcome this issue, we further proposed several types of assistance suits to improve practical usability based on four design principles:

(1) We focused on assisting not only the lower back, but also the arm muscles because lower-back injuries can be directly caused by arm-muscle fatigue [14].

(2) The belt layout must be concealable to prevent hazards in daily tasks.

(3) The structure must be adjustable to deal with different body dimensions of individual users and the weight of the carried load.

(4) The close-fitting characteristic of the suit is important for preventing the deformation of clothing under the force generated by the elastic component. In other words, a close-fitting suit can increase the effectiveness of assistance.

Two assistive suits were proposed, as shown in **Fig. 1**, based on the design principles.

2.1. Prototype-1 and Prototype-2

Worker-wear assistance suits, called Prototype-1 and Prototype-2, were proposed [13]. The difference between them was the spring coefficients of the rubber belts. The spring coefficient of Prototype-2 suit was approximately twice that of Prototype-1. The belt structure can be hidden under worker wear. The user can easily adjust the pretension of the rubber belts by pulling the nylon belts in front of the chest to adjust the back assistance belts and the belts near the waist to adjust the arm-muscle assistance belts. The arm assistive belts were connected from the elbow joint to the back of the waist and fixed on the personal leather belts. The cross-type assistive belts were connected from the front of the waist through the shoulder to the sole.

2.2. Prototype-3

The Prototype-3 suit was proposed to merge the adjusting belts in the same place for easy adjustment. The suit merged the adjusting belts for arm and back assistance on a waist belt. This suit is composed of a non-deformable fabric base and rubber and nylon belts. The belt structure can be hidden under the subject's personal clothes.

However, the subjects reported experiencing discomfort while tightening the belts. During the development period, we observed that the close-fitting characteristic is important because the assistive force generated by the rubber belts can be strongly influenced by the deformation of the fabric base. The deformation of the rubber belts can be reduced directly when the fabric base is deformed at the fixed points. Moreover, the assistive force can be decreased further because of Hooke's law. Therefore, we again designed a close-fitting assistive suit in 2018. Compared with the Prototype-3 suit, the structure of the belt layout was drastically modified.

Considering the practical motion in daily tasks, the new belt layout can use human motion intention to store the elastic energy and further release the energy to assist the user. Therefore, we drastically modified the belt structure based on the user's motion intention. Especially, the arm and back assistive belts were improved.

3. Close-Fitting Assistive Suit

A close-fitting assistive suit, called e.z.UP®, was proposed. This suit consisted mainly of woven rubber belts,

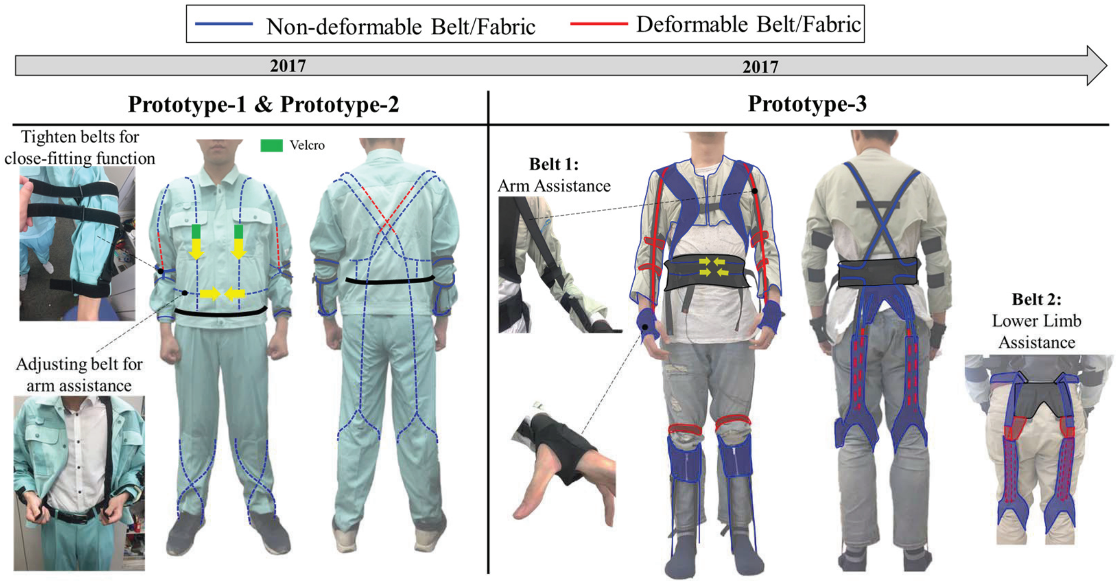


Fig. 1. Proposed assistive suit during the development period.

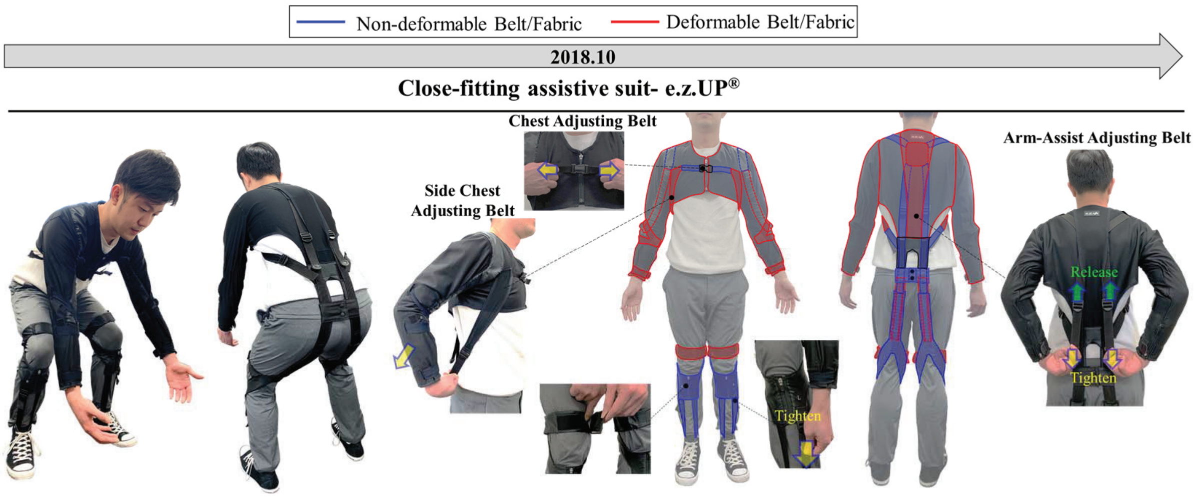


Fig. 2. Close-fitting assistive suit with adjustable structures – e.z.UP®.

nylon belts, and deformable and non-deformable fabrics, as shown in **Fig. 2**. The suit weighed 0.75 kg, and had the same weight with a jacket. The modification and improvement of e.z.UP® were demonstrated in the waist belt compared with the Prototype-3 suit. Additionally, the adjustability of Belt 2 of e.z.UP® was canceled because it can adequately generate the assistive force based on the user's posture. Compared with the previously proposed suits, deformable fabrics were considered to realize the close-fitting requirement. Even if the suit has a close-fitting characteristic, we continuously considered the tunability of the suit, as each human body wearing the same size still exhibits a slight difference. Three adjustable belts located at the chest, the side of the torso, and shanks were designed to satisfy the close-fitting property (**Fig. 2**). The user can also adjust the elongation of the rubber belts connected with the nylon belt at the back to adjust the arm assistive force further. The side-adjusting and chest-adjusting belts were used to make the suit fit with the user's body and achieve the close-fitting characteristic. The adjusting belt located in front of the shank can be adjusted to fit the height of the fixed point of the knee, because different users have different body dimensions.

Additionally, novel structures, a quadrilateral structure, and a two-layer structure, were proposed considering waist-twisting motions and adequate back assistance, as shown in **Fig. 3**. The assistive structure of the proposed suit can mainly be divided into two parts:

(1) The belt for arm-muscle assistance, called Belt 1, is shown in **Fig. 4(a)**. By connecting the belt from the elbow through the shoulder to the back of the knee, it can be pulled and extended while bending the knee and performing leaning trunk motions. It indicates

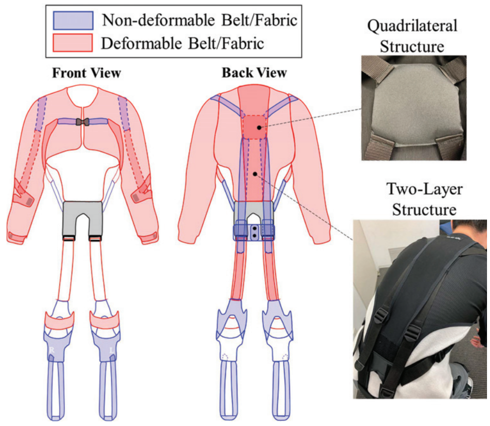
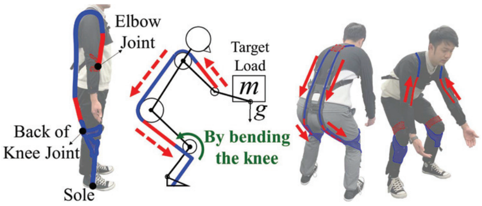
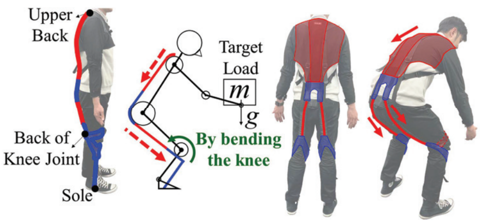


Fig. 3. Configuration of the close-fitting assistance suit.

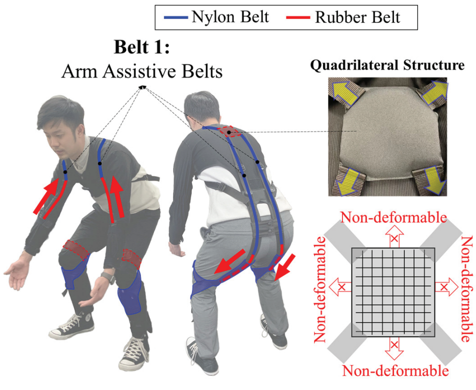


(a) Belt 1 for arm assistance

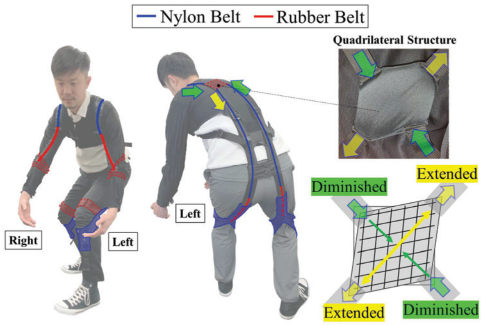


(b) Belt 2 for back assistance

Fig. 4. Concepts of arm and back assistance belts.



(a) Without twisting waist motion



(b) Twisting waist motion

Fig. 5. Assistive mechanism of the quadrilateral structure.

that the layout is designed based on the user's intention, and it automatically assists the user's arm muscle while he/she intends to lift/lower the target load.

(2) The belt for back assistance, called Belt 2, is shown in **Fig. 4(b)**. The belt was connected from the upper back to the back of the knee for the assistance of the back muscle. Similar to Belt 1, according to the user's lifting intention, Belt 2 can be deformed and it assists the user further.

In the following subsections, Belt 1 and Belt 2 are introduced in detail with the two novel structures, a quadrilateral structure and a two-layer structure, connected with Belt 1 and Belt 2, respectively.

3.1. Belt 1: Arm Assistance

The belt used mainly for arm assistance, called Belt 1, was connected with three elastic components by the nylon belts, two rubber belts located on biceps brachii (BB) and BFS muscles, and the proposed deformable fabric called quadrilateral structure shown in **Fig. 5**. Because of the woven pattern of the quadrilateral structure, its shape cannot be deformed in the horizontal and vertical directions (**Fig. 5(a)**). In other words, the quadrilateral structure is viewed as non-deformable fabric while the user performs a motion without twisting his/her waist. When the user turns his/her torso and twists his/her waist to pick up a target on the side, the elongation of the rubber, strongly related to the assistive force, may be influenced by the belt deformation due to the user's posture (**Fig. 5(b)**). The proposed quadrilateral structure can be deformed along the diagonal direction because of the woven pattern. It can prevent and compensate for the loosening of the arm assistance belt when the user twists his/her waist and upper trunk. Comparing the loading of the waist and the arm, the waist bears greater burden because of the mass of the trunk and load.

The lengths of the rubbers located at the BB and BFS muscles were 0.22 m with two layers and 0.19 m with one layer, which had the effective spring coefficients of 325.2 N/m ($k_{belt1,1}$) and 178.9 N/m ($k_{belt1,2}$), respectively. Due to the series connection of the two elastic belts, the effective spring coefficient of the belt for arm assistance was 115.4 N/m.

3.2. Belt 2: Back Assistance

For the back assistance, the load of the back and the deformation of the skin, simultaneously, increase as the back bends. Therefore, in our previous paper [12], a nonlinear spring made of a rubber belt was proposed as a fu-

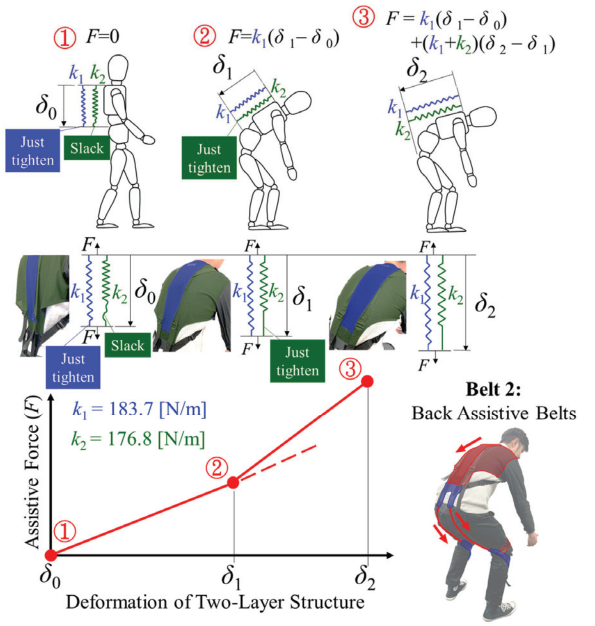


Fig. 6. Assistive mechanism of the two-layer structure.

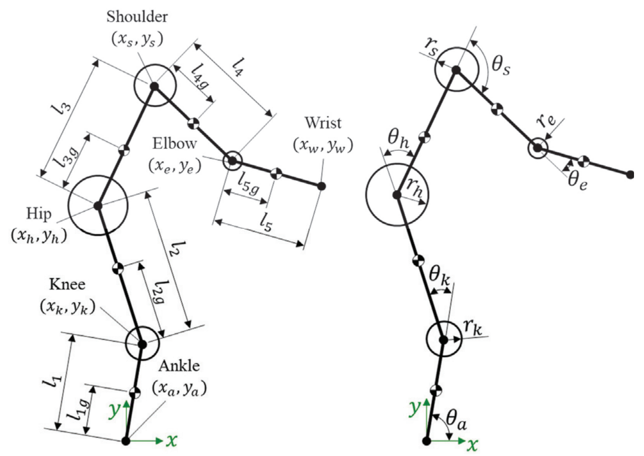


Fig. 7. Definitions of a human model.

Table 1. Averaged limb lengths in the human model [15].

Length of each limb [m]				
l_1	l_2	l_3	l_4	l_5
0.3687	0.3968	0.5215	0.2986	0.2373

Table 2. Averaged joint radius in the human model [15].

Radius of each joint [m]				
r_k	r_h	r_s	r_e	r_w
0.0576	0.1047	0.0766	0.0459	0.0266

ture work. In this paper, we propose a stiffness changeable structure consisting of two deformable elastic fabrics, called the two-layer structure (**Fig. 6**). The structure provides lighter assistance when the user stands straight to prevent the burden of an inversed muscle, such as the rectus abdominis muscle. While the user bends his/her trunk, the outer layer is deformed, and the inner layer is slack. Further, as the user tends to bend or lean forward and lift the load, the inner and outer layers are both extended and activated along with the back skin. In contrast, our proposed two-layer structure can increase the assistive force according to the user's motion gradually and automatically. The spring coefficients of the outer layer (k_1) and inner layer (k_2) were 183.7 N/m and 176.8 N/m, respectively.

The belt located at the thigh muscle and connected from the lower back to the back of the knee joint was considered for providing the tension force to the two-layer structure, but also for the lower-limb assistance parallel with Belt 1 (**Fig. 5(a)**). The rubber length was 0.24 m with an effective spring coefficient of 232.0 N/m ($k_{belt2,2}$). Due to the series connection of the two-layer structure and the thigh belt, the equivalent spring coefficient is 102.5 N/m when the deformation of the two-layer structure smaller than 0.02 m (δ_1) and 141.2 N/m when the deformation of the two-layer structure is larger than 0.02 m (δ_1).

4. Simulation

The proposed suit has a close-fitting property. In other words, the belt deformation was strongly and simultaneously influenced by the user's postures. The assistive force generated by the elastic component can be affected further by the deformation of the rubber belt because of Hooke's law. Therefore, a simulation was conducted to obtain the belt deformation, especially for the arm-muscle assistive belts (Belt 1), of Prototype-3 and e.z.UP® based on a practical motion.

4.1. Human Model and Boundary Conditions

4.1.1. Human Model

The simulation was conducted with a human model to evaluate the feasibility of the proposed suit with the designed elastic structure pattern. Consider that the user may be male/female and young/elderly. The model was proposed based on the averaged body dimensions of Japanese young adults aged from 18 to 30 years and the elderly aged from 60 to 88 years, as shown in **Fig. 7**. **Table 1** presents the averaged lengths of the shank (l_1), thigh (l_2), trunk (l_3), upper arm (l_4), and forearm (l_5). The average mass of the human model (m) was 57.2 kg. We assumed herein that each joint has its corresponding radius, which is also referred to as the average body dimension [15]. **Table 2** shows the radii of the knee (r_k), hip (r_h), shoulder (r_s), and elbow (r_e) joints [15]. The corresponding position of the center of gravity (COG) of each limb was obtained from Leva's technical note [16]. The location of the COG of each limb is defined in **Fig. 7**, where l_{1g}, l_{2g}, l_{3g}, l_{4g}, and l_{5g} were $0.5541 \cdot l_1$, $0.5905 \cdot l_2$, $0.5514 \cdot l_3$, $0.5772 \cdot l_4$, and $0.4574 \cdot l_5$, respectively. Drill et al. [17] stated that the mass of each limb defined as m_1, m_2, m_3, m_4, and m_5 was $0.0878m$, $0.2236m$, $0.5342m$, $0.0648m$, and $0.0362m$, respectively.

The ankle joint (x_a, y_a) was defined as the original point $(0,0)$ in the coordination system. The position of the knee joint (x_k, y_k), hip joint (x_h, y_h), shoulder joint (x_s, y_s), and elbow joint (x_e, y_e) in the sagittal plane can be presented as a vector $\{\boldsymbol{x}_{human}\ \boldsymbol{y}_{human}\}^{\mathrm{T}} = \{x_k\ x_h\ x_s\ x_e\ x_w\ y_k\ y_h\ y_s\ y_e\ y_w\}^{\mathrm{T}} \in \mathrm{R}^{10}$ and calculated as follows:

$$\begin{Bmatrix} \boldsymbol{x}_{human} \\ \boldsymbol{y}_{human} \end{Bmatrix} = \begin{bmatrix} C_1 \\ S_1 \end{bmatrix} \{l_1 \quad l_2 \quad l_3 \quad l_4 \quad l_5\}^{\mathrm{T}}, \quad . \quad (1)$$

where $\{l_1\ l_2\ l_3\ l_4\ l_5\}^{\mathrm{T}} \in \mathrm{R}^5$ denotes the length vector. $C_1 \in \mathrm{R}^{5\times5}$ and $S_1 \in \mathrm{R}^{5\times5}$ are the lower triangular matrices consisting of cosine and sine, including each joint angle (θ_a, θ_k, θ_h, θ_s, and θ_e), respectively. They can be written as follows:

$$C_1 = \begin{bmatrix} \cos\theta_a & 0 & 0 & 0 & 0 \\ \cos\theta_a & \cos\theta_{h1} & 0 & 0 & 0 \\ \cos\theta_a & \cos\theta_{h1} & \cos\theta_{h2} & 0 & 0 \\ \cos\theta_a & \cos\theta_{h1} & \cos\theta_{h2} & \cos\theta_{h3} & 0 \\ \cos\theta_a & \cos\theta_{h1} & \cos\theta_{h2} & \cos\theta_{h3} & \cos\theta_{h4} \end{bmatrix} \in \mathrm{R}^{5\times5}$$

and

$$S_1 = \begin{bmatrix} \sin\theta_a & 0 & 0 & 0 & 0 \\ \sin\theta_a & \sin\theta_{h1} & 0 & 0 & 0 \\ \sin\theta_a & \sin\theta_{h1} & \sin\theta_{h2} & 0 & 0 \\ \sin\theta_a & \sin\theta_{h1} & \sin\theta_{h2} & \sin\theta_{h3} & 0 \\ \sin\theta_a & \sin\theta_{h1} & \sin\theta_{h2} & \sin\theta_{h3} & \sin\theta_{h4} \end{bmatrix} \in \mathrm{R}^{5\times5},$$

where $\theta_{h1} = \theta_a + \theta_k$, $\theta_{h2} = \theta_a + \theta_k - \theta_h$, $\theta_{h3} = \theta_a + \theta_k - \theta_h - \theta_s$ and $\theta_{h4} = \theta_a + \theta_k - \theta_h - \theta_s + \theta_e$.

4.1.2. Boundary Conditions

The assistive force can be generated by the rubber deformation; hence, the simulations were considered for a comparison with the belt structure between Prototype-3 and e.z.UP®. The boundary conditions of e.z.UP® and Prototype-3 were defined based on the layouts of the proposed suits and the human model (**Figs. 8** and **9**, respectively). The difference between the belt structures of Prototype-3 and e.z.UP® was the arm assistive belts (Belt 1). The corresponding coordination of each defined point can be presented as a vector $\{x_1\ x_2\ x_3\ \cdots\ x_{10}\ y_1\ y_2\ y_3\ \cdots\ y_{10}\}^{\mathrm{T}} \in \mathrm{R}^{20}$, which can be written as $\{\boldsymbol{x}_{belt}\ \boldsymbol{y}_{belt}\}^{\mathrm{T}} \in \mathrm{R}^{20}$ and calculated as follows:

$$\begin{Bmatrix} \boldsymbol{x}_{belt} \\ \boldsymbol{y}_{belt} \end{Bmatrix} = \begin{bmatrix} B & 0 \\ 0 & B \end{bmatrix} \begin{Bmatrix} \boldsymbol{x}_{human} \\ \boldsymbol{y}_{human} \end{Bmatrix} + \begin{bmatrix} C_2 \\ S_2 \end{bmatrix} \boldsymbol{r}, \quad (2)$$

where $\boldsymbol{r} = \{r_k\ r_h\ r_s\ r_e\ r_w\ l_c\}^{\mathrm{T}} \in \mathrm{R}^6$ denotes the length vector consisting of the averaged radii of each joint. l_c can be written as $l_c = (a^2 + b^2)^{0.5}$, and a and b are the thickness of torso and the navel height from the hip joint on average [15], respectively. $B \in \mathrm{R}^{10\times5}$ is a logical matrix consisting of 0 and 1, and it can be expressed as

$$B = \begin{bmatrix} 1\,0\,0\,0\,0 \\ 0\,1\,0\,0\,0 \\ 0\,1\,0\,0\,0 \\ 0\,0\,1\,0\,0 \\ 0\,0\,1\,0\,0 \\ 0\,0\,0\,1\,0 \\ 0\,0\,0\,0\,1 \\ 0\,0\,1\,0\,0 \\ 0\,1\,0\,0\,0 \\ 0\,1\,0\,0\,0 \end{bmatrix} \in \mathrm{R}^{10\times5}.$$

$C_2 \in \mathrm{R}^{10\times6}$ and $S_2 \in \mathrm{R}^{10\times5}$ are triangular matrices consisting of cosine and sine with each joint angle (θ_a, θ_k, θ_h, θ_s, and θ_e), respectively. They can be written as follows:

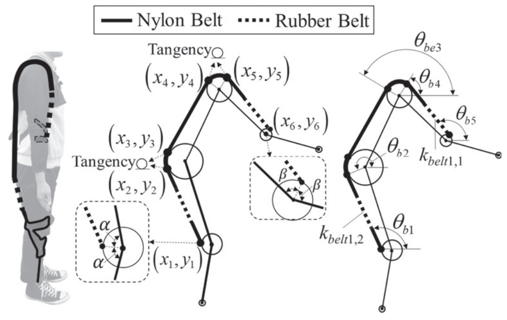
$$C_2 = \begin{bmatrix} \cos\theta_{b1} & 0 & 0 & 0 & 0 & 0 \\ 0 & \cos\theta_{b2} & 0 & 0 & 0 & 0 \\ 0 & \cos\theta_{be3} & 0 & 0 & 0 & 0 \\ 0 & 0 & \cos\theta_{be3} & 0 & 0 & 0 \\ 0 & 0 & \cos\theta_{b4} & 0 & 0 & 0 \\ 0 & 0 & 0 & \cos\theta_{b5} & 0 & 0 \\ 0 & 0 & 0 & 0 & \cos\theta_{bp6} & 0 \\ 0 & 0 & \cos\theta_{bp3} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \cos\theta_{b7} \\ 0 & \cos\theta_{b6} & 0 & 0 & 0 & 0 \end{bmatrix}$$
$$\in \mathrm{R}^{10\times6}$$

and

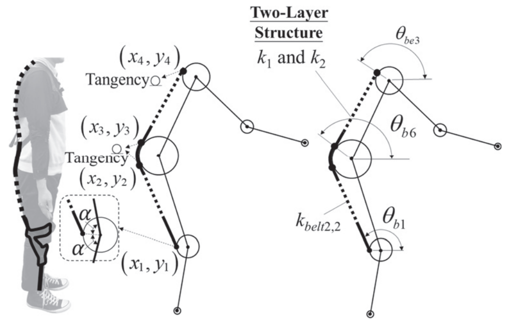
$$S_2 = \begin{bmatrix} \sin\theta_{b1} & 0 & 0 & 0 & 0 & 0 \\ 0 & \sin\theta_{b2} & 0 & 0 & 0 & 0 \\ 0 & \sin\theta_{be3} & 0 & 0 & 0 & 0 \\ 0 & 0 & \sin\theta_{be3} & 0 & 0 & 0 \\ 0 & 0 & \sin\theta_{b4} & 0 & 0 & 0 \\ 0 & 0 & 0 & \sin\theta_{b5} & 0 & 0 \\ 0 & 0 & 0 & 0 & \sin\theta_{bp6} & 0 \\ 0 & 0 & \sin\theta_{bp3} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \sin\theta_{b7} \\ 0 & \sin\theta_{b6} & 0 & 0 & 0 & 0 \end{bmatrix}$$
$$\in \mathrm{R}^{10\times6}$$

where θ_{b1}, θ_{b2}, θ_{be3}, θ_{b4}, θ_{b5}, θ_{b6}, θ_{b7}, θ_{bp3} and θ_{bp6} can be expressed as follows, respectively.

$$\begin{aligned} \theta_{b1} &= \theta_a + \theta_k + \frac{\pi - \theta_k}{2}, \\ \theta_{b2} &= \theta_a + \theta_k + \frac{\pi}{2} - \tan^{-1}\left(\frac{|y_k - y_h|}{|x_k - x_h|}\right), \\ \theta_{be3} &= \theta_a + \theta_k - \theta_h \\ &\quad - \tan^{-1}\left(\frac{\sqrt{(x_s - x_h)^2 + (y_s - y_h)^2}}{|r_h - r_s|}\right), \end{aligned}$$



(a) Belt 1 for arm assistance



(b) Belt 2 for back assistance

Fig. 8. Boundary conditions and defined angles of e.z.UP®.

$$\theta_{b4} = \tan^{-1}\left(\frac{\sqrt{(x_e-x_s)^2+(y_s-y_e-r_e)^2-r_s{}^2}}{r_s}\right) - \tan^{-1}\left(\frac{y_s-y_e-r_e}{x_e-x_s}\right),$$

$$\theta_{b5} = \tan^{-1}\left(\frac{x_s-x_e}{l_4}\right),$$

$$\theta_{b6} = \theta_a+\theta_k-\theta_h+\cos^{-1}\left(\frac{b}{\sqrt{a^2+b^2}}\right) + \cos^{-1}\left(\frac{r_h}{\sqrt{a^2+b^2-r_h{}^2}}\right),$$

$$\theta_{b7} = \theta_a+\theta_k-\theta_h+\cos^{-1}\left(\frac{b}{\sqrt{a^2+b^2}}\right),$$

$$\theta_{bp3} = \pi+\theta_a+\theta_k-\theta_h-\tan^{-1}\left(\frac{a}{l_3-b}\right) - \tan^{-1}\left(\frac{l_b}{r_s}\right),$$

$$\theta_{bp6} = \frac{\pi}{2}-\tan^{-1}\left(\frac{y_e-y_w}{x_w-x_e}\right).$$

The variation of each belt length can be derived further using Eq. (2).

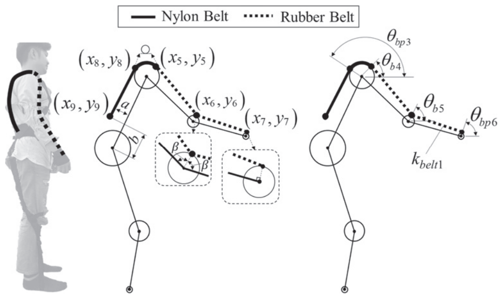
4.1.3. Simulation Results

A lifting motion was recorded, as shown in **Fig. 10**, to obtain the length variation of the belts and compare the difference of the layouts. The motion was also used for the simulation in the following subsection. Through substituting the angle variation of each joint into Eqs. (1) and (2), the motion and elongation of Belt 1 and Belt 2 of both e.z.UP® and Prototype-3 can be simulated, as shown in the results of **Fig. 11**. **Fig. 12** shows the corresponding deformations of the belts. The elongation of the belts of both suits can be calculated using the following equations. For the deformation of Belt 1 ($\delta_{belt1,e.z.UP}$) and Belt 2 ($\delta_{belt2,e.z.UP}$) of e.z.UP®, the equations can be written as follows:

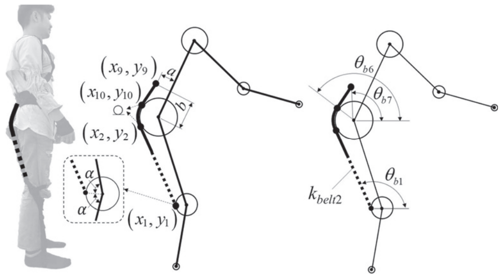
$$\delta_{belt1,e.z.UP} = \sqrt{(x_2-x_1)^2+(y_2-y_1)^2}+r_h(\theta_{b2}-\theta_{b6}) + \sqrt{(x_4-x_3)^2+(y_4-y_3)^2}+r_s(\theta_{be3}-\theta_{b4}) + \sqrt{(x_6-x_5)^2+(y_6-y_5)^2}-l_{initial,Belt1},$$

and

$$\delta_{belt2,e.z.UP} = \sqrt{(x_2-x_1)^2+(y_2-y_1)^2}+r_h(\theta_{b2}-\theta_{b6}) + \sqrt{(x_8-x_7)^2+(y_8-y_7)^2}-l_{initial,Belt2},$$



(a) Belt 1 for arm assistance



(b) Belt 2 for back assistance

Fig. 9. Boundary conditions and defined angles of Prototype-3.

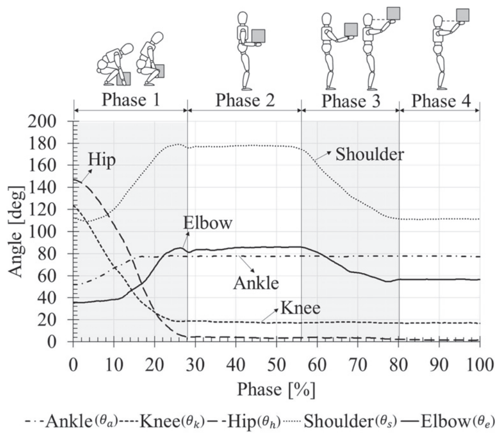
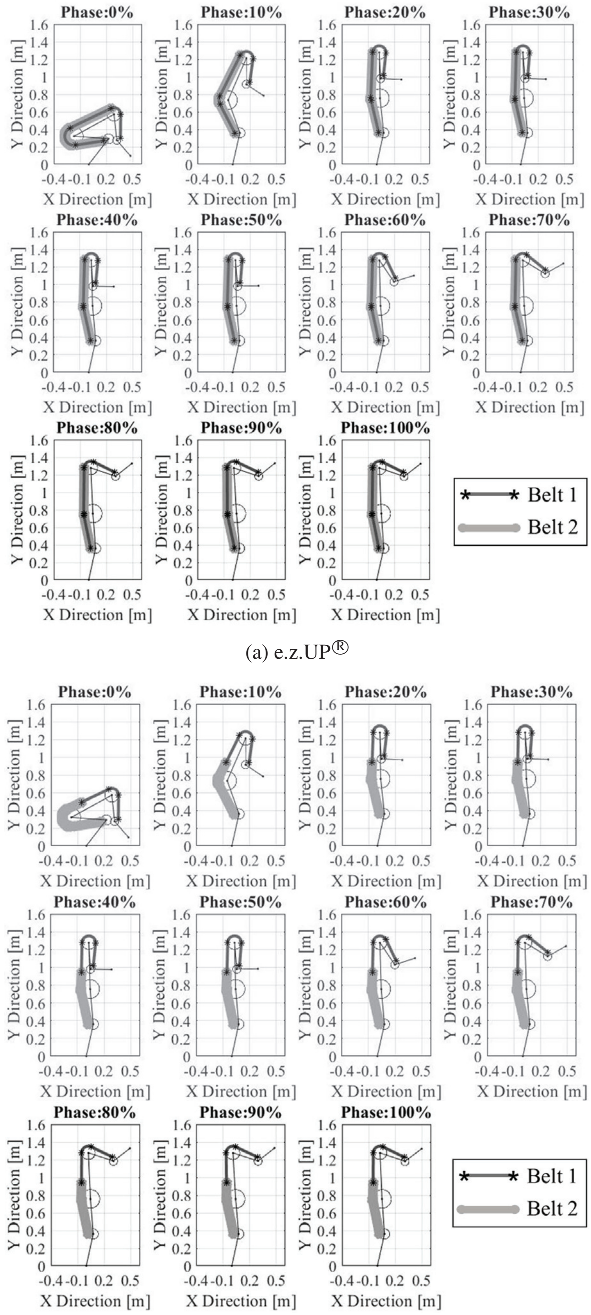


Fig. 10. Angular variation of a lifting motion in the simulation.



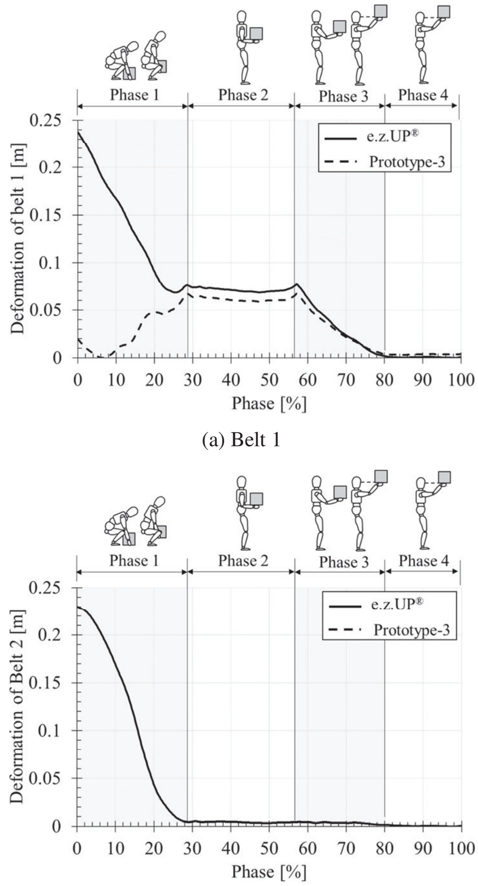
(a) e.z.UP®

(b) Prototype-3

Fig. 11. Simulation of a lifting motion by wearing e.z.UP® and Prototype-3.

where $l_{initial,Belt1}$ and $l_{initial,Belt2}$ are the initial lengths of Belt 1 and Belt 2 of e.z.UP® with the values of 1.344 m and 0.920 m, respectively. For the deformation of Belt 1 ($\delta_{belt1,proto3}$) and Belt 2 ($\delta_{belt2,proto3}$) of Prototype-3, the corresponding equations can be written as follows:

$$\delta_{belt1,proto3} = \sqrt{(x_8 - x_9)^2 + (y_8 - y_9)^2} + \sqrt{(x_5 - x_6)^2 + (y_5 - y_6)^2} + r_s\left(\theta_{bp3} - \theta_{b4}\right) + \sqrt{(x_6 - x_{10})^2 + (y_6 - y_{10})^2} - l'_{initial,Belt1},$$



(a) Belt 1

(b) Belt 2

Fig. 12. Deformation of the belts with Prototype-3 and e.z.UP®.

and

$$\delta_{belt2,proto3} = \sqrt{(x_8 - x_7)^2 + (y_8 - y_7)^2} + \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2} + r_h\left(\theta_{b2} - \theta_{b6}\right) - l'_{initial,Belt2},$$

where the $l'_{initial,Belt1}$ and $l'_{initial,Belt2}$ are the initial lengths of Belt 1 and Belt 2 of Prototype-3 suit with the values of 0.986 m and 0.579 m, respectively.

Comparing the arm assistive belts, Belt 1 of e.z.UP® showed a greater deformation than that of Prototype-3, especially during Phase 1 (**Fig. 12(a)**), because the belt layout of e.z.UP® can be influenced by the lower limb. These results indicate that the assistive force can be generated further while the user performs a lifting motion. In the practical scene, when lifting the load from the ground, a human tends to output a higher force to generate the momentum, which may cause injuries during Phase 1. Therefore, a higher belt deformation can generate a greater assistive force. During Phase 2, after lifting the load and standing straight, the rubber deformation tends to the minimum to prevent additional burden. When the user desires to lift during Phases 3 and 4, the assistive force can be adequately generated because of the belt deformation. Belt 2 of Prototype-3 and that of e.z.UP® were the same

Table 3. Spring coefficients of Belt 1 and Belt 2 on Prototype-3 and e.z.UP®.

		Variable	Spring coefficient [N/m]
e.z.UP®	Belt 1	$k_{belt1,1}$	325.2
		$k_{belt1,2}$	176.8
	Belt 2	$k_{belt2,1}$	$k_1 = 183.7$ ($\delta_1 \leq 0.02$ m)
			$k_1 + k_2 = 360.5$ ($\delta_1 > 0.02$ m)
		$k_{belt2,2}$	232.0
Prototype-3	Belt 1	k_{belt1}	172.0
	Belt 2	k_{belt2}	113.2

(i.e., fixed from the lower back to the back of the knee); therefore, the deformations of Belt 2 were also the same (**Fig. 12(b)**). As in Belt 1, Belt 2 can maintain a higher tension force to maintain the pretension of the two-layer structure while the user tends to lift the load. Comparing the waist-belt types of Prototype-3 and Belt 1 of e.z.UP®, Belt 1 is proven to assist the user adequately as needed.

4.2. Torques of the Joint

Each joint of the human body is related to a pair of muscle groups, such as the BB and triceps brachii muscles, which are related to the motion of elbow flexion and extension motions, respectively. Therefore, to mimic the assistive efficiency of wearing our proposed suit, e.z.UP®, the torque of each joint was evaluated based on the proposed human model with average body dimensions shown in **Fig. 7**. The dynamic properties of the elastic materials (e.g., hysteresis) were ignored; hence, the torque evaluation of each joint was considered in static. Based on the human model and the boundary conditions while wearing the suit shown in **Figs. 8** and **9**, the torques of each joint can be written in vector form as $\boldsymbol{\tau} = \{\tau_e\ \tau_s\ \tau_h\ \tau_k\ \tau_a\}^{\mathrm{T}} \in \mathrm{R}^5$ and presented as:

$$\boldsymbol{\tau} = A_1 M \{l_5\ l_4\ l_3\ l_2\ l_1\}^{\mathrm{T}} g + A_2 \boldsymbol{l}_r f_{Belt1} + A_3 \boldsymbol{l}_r f_{Belt2}, \quad (3)$$

where f_{Belt1} and f_{Belt2} are the tension forces generated by the deformations of Belt 1 and Belt 2 and their spring coefficients, respectively. Based on Hooke's law, the assistive forces of each suit can be expressed using the corresponding spring coefficients shown in **Table 3**. For the assistive forces generated by e.z.UP®, the equations of the assistive forces generated by Belt 1 (f_{Belt1}) and Belt 2 (f_{Belt2}) can be separately written as follows:

$$f_{Belt1} = \frac{k_{belt1,1} k_{belt1,2}}{k_{belt1,1} + k_{belt1,2}} \cdot \delta_{Belt1,e.z.UP},$$

$$f_{Belt2} = \begin{cases} \dfrac{k_1 k_{belt2,1}}{k_1 + k_{belt2,1}} \cdot \delta_{Belt2,e.z.UP}, \quad (\delta_{Belt2,e.z.UP} \leq \delta_1), \\ \dfrac{k_1 k_{belt2,1}}{k_1 + k_{belt2,1}} \cdot \delta_1 + \dfrac{(k_1 + k_2) k_{belt2,1}}{k_1 + k_2 + k_{belt2,1}} \cdot \delta_{Belt2,e.z.UP}, \\ \qquad (\delta_{Belt2,e.z.UP} > \delta_1). \end{cases}$$

Table 4. Corresponding parameters in matrix A_2.

Parameter	Corresponding equation
e.z.UP®	
$a_{2,1}$	$-\sin(\theta_5 + \theta_7)$
$a_{2,2}$	$\sin(\theta_8 - \theta_5)$
$a_{2,3}$	$\sin(\theta_9 + \theta_k - \theta_h - \theta_a)$
$a_{2,4}$	$-\sin(\theta_{10} + \theta_a + \theta_k)$
$a_{2,5}$	1
$a_{2,6}$	0
Prototype-3	
$a_{2,1}$	$-\sin(\theta_5 + \theta_6)$
$a_{2,2}$	$-\sin(\theta_5 - \theta_7)$
$a_{2,3}$	$-\sin(\theta_5 + \theta_a + \theta_k - \theta_h)$
$a_{2,4}$	$\sin(\theta_5 + \theta_a + \theta_k - \pi) + \sin(\theta_{10} - \theta_a - \theta_k + \pi)$
$a_{2,5}$	0
$a_{2,6}$	$-\sin(\theta_5 + \theta_a) - \sin(\theta_{10} - \theta_a)$

For the assistive forces generated by Belt 1 (f_{Belt1}) and Belt 2 (f_{Belt2}) of Prototype-3, the equations can be written as follows:

$$f_{Belt1} = k_{belt1} \delta_{Belt1,proto3},$$

$$f_{Belt2} = k_{belt2} \delta_{Belt2,proto3}.$$

$A_1 \in \mathrm{R}^{5\times5}$ is the angle matrix consisting of the triangular relationship, and can be expressed as follows:

$$A_1 = \begin{bmatrix} \cos\theta_1 & 0 & 0 & 0 & 0 \\ \cos\theta_1 & \cos\theta_2 & 0 & 0 & 0 \\ \cos\theta_1 & \cos\theta_2 & \cos\theta_3 & 0 & 0 \\ \cos\theta_1 & \cos\theta_2 & \cos\theta_3 & \cos\theta_4 & 0 \\ \cos\theta_1 & \cos\theta_2 & \cos\theta_3 & \cos\theta_4 & \cos\theta_a \end{bmatrix} \in \mathrm{R}^{5\times5},$$

where $\theta_1 = \theta_h + \theta_s - \theta_a - \theta_k - \theta_e$, $\theta_2 = \pi/2 + \theta_a + \theta_k - \theta_s - \theta_h$, $\theta_3 = \theta_a + \theta_k - \theta_h$ and $\theta_4 = \pi - \theta_a - \theta_k$. $A_2 \in \mathrm{R}^{5\times5}$ is the angle matrix related to the assistive force generated by Belt 1. It can be expressed as follows:

$$A_2 = \begin{bmatrix} a_{2,1} & 0 & 0 & 0 & 0 \\ a_{2,1} & a_{2,2} & 0 & 0 & 0 \\ a_{2,1} & a_{2,2} & a_{2,3} & 0 & 0 \\ a_{2,1} & a_{2,2} & a_{2,3} & a_{2,4} & a_{2,5} \\ a_{2,1} & a_{2,2} & a_{2,3} & a_{2,4} & a_{2,5} \end{bmatrix} \in \mathrm{R}^{5\times5}.$$

In the case of wearing e.z.UP® and Prototype-3, the elements in matrix $A_2 \in \mathrm{R}^{5\times5}$ are shown in **Table 4**. The matrix related to the assistive force generated by Belt 2 can be written as $A_3 \in \mathrm{R}^{5\times5}$ and expressed as follows:

$$A_3 = \begin{bmatrix} a_{3,1} & 0 & 0 & 0 & 0 \\ a_{3,1} & a_{3,2} & 0 & 0 & 0 \\ a_{3,1} & a_{3,2} & a_{3,3} & 0 & 0 \\ a_{3,1} & a_{3,2} & a_{3,3} & a_{3,4} & a_{3,5} \\ a_{3,1} & a_{3,2} & a_{3,3} & a_{3,4} & a_{3,5} \end{bmatrix} \in \mathrm{R}^{5\times5}.$$

Table 5. Corresponding parameters in matrix A_3.

Parameter	Corresponding equation
e.z.UP®	
$a_{3,1}$	0
$a_{3,2}$	0
$a_{3,3}$	$\sin(\theta_9+\theta_k-\theta_a-\theta_h)$
$a_{3,4}$	1
$a_{3,5}$	$-\sin(\theta_{10}+\theta_a+\theta_k)$
$a_{3,6}$	0
Prototype-3	
$a_{3,1}$	0
$a_{3,2}$	0
$a_{3,3}$	0
$a_{3,4}$	0
$a_{3,5}$	$\sin(\theta_8-\theta_9)$
$a_{3,6}$	$\sin(\theta_9-\theta_a)$

The elements in A_3 are shown in **Table 5**. θ_5, θ_6, θ_7, θ_8, θ_9, and θ_{10} can be expressed as follows:

$$\theta_5 = \tan^{-1}\left(\frac{y_5-y_6}{x_6-x_5}\right), \quad \theta_6 = \cos^{-1}\left(\frac{x_w-x_e}{l_5}\right),$$

$$\theta_7 = \sin^{-1}\left(\frac{y_6-y_e}{r_e}\right), \quad \theta_8 = \cos^{-1}\left(\frac{x_e-x_s}{l_4}\right),$$

$$\theta_9 = \sin^{-1}\left(\frac{y_4-y_3}{\sqrt{(x_3-x_4)^2+(y_3-y_4)^2}}\right),$$

$$\theta_{10} = \sin^{-1}\left(\frac{y_2-y_1}{\sqrt{(x_2-x_1)^2+(y_2-y_1)^2}}\right).$$

$M \in \mathrm{R}^{5\times5}$ is a mass matrix consisting of the masses of the load and each limb.

$$M = \begin{bmatrix} M_1 & 0 & 0 & 0 & 0 \\ 0 & M_2 & 0 & 0 & 0 \\ 0 & 0 & M_3 & 0 & 0 \\ 0 & 0 & 0 & M_4 & 0 \\ 0 & 0 & 0 & 0 & M_5 \end{bmatrix} \in \mathrm{R}^{5\times5},$$

where $M_1 = m_{load} + 0.4574 \cdot m_5$, $M_2 = m_{load} + m_5 + 0.5772 \cdot m_4$, $M_3 = m_{load} + m_5 + m_4 + 0.5514 \cdot m_3$, $M_4 = -(m_{load}+m_5+m_4+m_3+0.5905 \cdot m_2)$, and $M_5 = m_{load} + m_5 + m_4 + m_3 + m_2 + 0.5541 \cdot m_1$. $\boldsymbol{l}_r = \{r_e\ l_4\ l_3\ l_2\ r_k\}^{\mathrm{T}} \in \mathrm{R}^5$ are the length-radius vectors which include the corresponding force arm based on the boundary conditions. Using Eq. (3), the torques of each joint can be compared while wearing and not wearing e.z.UP®. We ignored the friction between the clothing and belts herein.

The simulation conditions are described here. The corresponding spring coefficients of Belt 1 and Belt 2 of e.z.UP® and Prototype-3 were 142.6 N/m and 232.0 N/m, respectively. The pretension of Belt 1 was 0.1 m and that of Belt 2 was 0 m, as it is only tightened while standing. The load weight was 10 kg and carried by both hands. Due to the two-dimensional human model, the load acting on the tip of the wrist joint was 5 kg. According to the belt deformation with the recorded motion, the influence of assistive force generated by the rubber belts and the torques of each joint can be calculated using Eq. (3). **Fig. 13** illustrates the simulation results of each joint's torque.

In Phase 1, the greatest assistive force appeared on each limb, which decreased the torques of joints while e.z.UP® was worn. It can prove that the assistive force can be provided adequately. The torques of each joint can be successfully decreased by wearing the suit, except for the hip and shoulder joints. In other words, the suit may not cause any additional burden on other joints while being worn. The torques of the ankle joint can be decreased, especially in Phase 1. Comparing the elbow joint and the other joints, assistance can be successfully provided in each phase. Due to the layout of the belts of e.z.UP®, not only the upper limb but also the lower limb can be assisted. The experimental results were obtained and compared with those of the previously proposed suits to verify the simulation results.

5. Experimental Evaluations

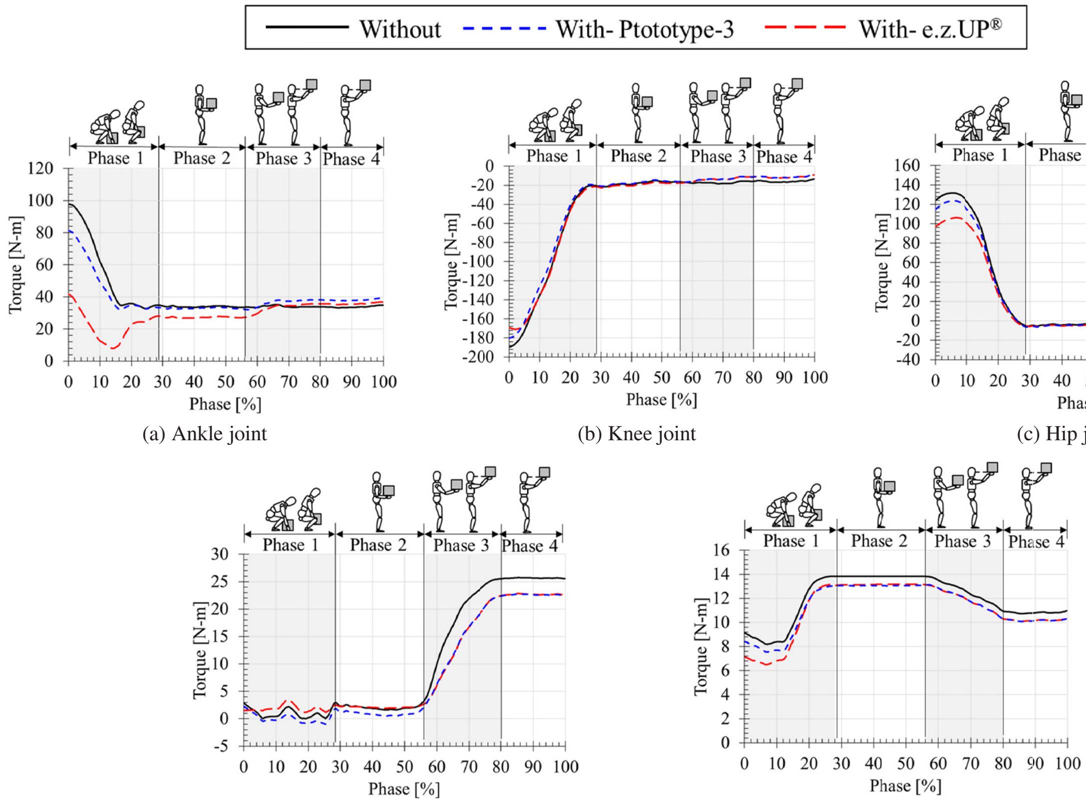
An experiment was conducted with the measurement of muscle activities to confirm the simulation results. Mainly, the arm and back muscles were compared with the three suits (Prototype-1, Prototype-2, and Prototype-3) and the newest suit (e.z.UP®) to verify whether the layout of belts of e.z.UP® was better than those of the above three suits. From the simulation results, the torque of the ankle joint can be decreased, especially in Phase 1. Therefore, the experiment can be separated into two parts, upper limb including arm and back muscles and lower-limb ankle plantar flexion motion.

5.1. Experimental Protocol and Conditions

5.1.1. Experimental Protocol

The experimental protocol shown in **Fig. 14** is the same as the motion in the simulation part. This motion can cover several daily tasks of manual handling workers, such as lifting the load from the ground and placing that load on the shelf. Each phase had a period of 5 s. The load weight for this experiment was 10 kg. The subjects were asked to lift the load from the ground to the height of the waist, maintain the angle of the elbow joint at approximately 90°, and then maintain this posture for 5 s. Then, they were asked to lift further upward until the bottom of the box reached the eye level.

Each subject was asked to perform the same motion thrice. The rest time between each set of experiments was 10 min. Before conducting the experiments, the subjects were asked to adjust the belt by themselves when they can feel the assistive force and move freely.



(a) Ankle joint (b) Knee joint (c) Hip joint

(d) Shoulder joint (e) Elbow joint

Fig. 13. Simulation results of the torque of each joint with and without using Prototype-3 and e.z.UP®.

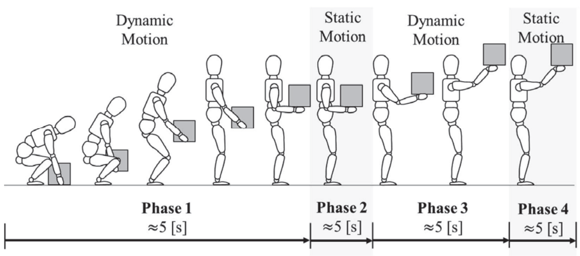


Fig. 14. Experimental protocol with a lifting motion.

5.1.2. Measured Muscle Groups

The activity of the back muscle must be considered as one of the measurement items to evaluate the effectiveness of the two-layer structure. The thoracic paraspinal muscle (PM), related to the motion of back stretching, was measured. The simulation results showed that the elbow joint had an apparent improvement in each phase. Therefore, the BB muscle was considered a measured muscle group related to the elbow flexion motion. Furthermore, in our previous study [12], we measured several parts of the muscle groups. The BB and PM muscles showed an evident improvement.

The lower-limb muscle activities were also considered and evaluated because the torque ankle joint can be successfully decreased, especially in Phase 1. According to the lifting motion in the experimental protocol, the ankle joint performs the plantar flexion of the foot. The tibialis anterior (TA), gastrocnemius (GAS), and soleus (SOL) muscles are related to the ankle motion. The TA muscle is related to the motion of the foot dorsiflexion. GAS and SOL muscles are related to the motion of plantar flexion of the foot. As the lifting motion is related to the foot plantar flexion motion, the GAS and SOL muscles were mainly the observed muscles. As a summary, the measured muscle groups are shown in **Fig. 15**.

5.1.3. Data Processing and *t*-Test Analysis

The maximum voluntary contraction (MVC) was measured in advance to find the maximum muscle activities of each muscle group of each subject. Accordingly, %MVC was calculated using integrated electromyography (iEMG) and MVC to eliminate the individual difference:

$$\%\mathrm{MVC} = \frac{\mathrm{iEMG}}{\mathrm{MVC}}. \qquad (4)$$

All the subjects underwent the experiments with the same experimental protocol. The measured iEMG data of each subject were calculated using a t-test statistical analysis. The p-value of the t-test was analyzed. A p-value less than 0.05 was used to judge the improvement of the muscle activities with and without the suits. The results indicated a confidence level above 95% to prove the effectiveness. Under the condition of a p-value lower than 0.05, the decreasing ratio (η) was calculated to com-

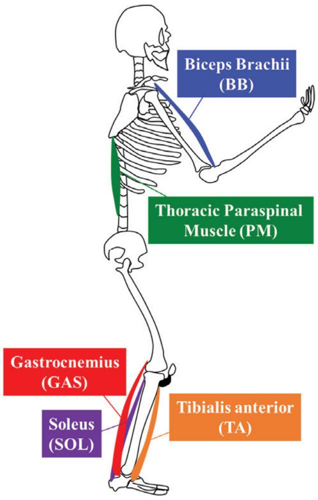


Fig. 15. Measured muscle groups for experimental evaluation.

pare the efficiency as follows:

$$\eta = \frac{\%\mathrm{MVC}_{without} - \%\mathrm{MVC}_{with}}{\%\mathrm{MVC}_{without}} \times 100\%, \quad . \quad . \quad (5)$$

where $\%\mathrm{MVC}_{without}$ and $\%\mathrm{MVC}_{with}$ denote the %MVC values with and without wearing the suit, respectively.

5.2. Experimental Results and Discussions

5.2.1. Upper-Limb Assistance

During the development period, we proposed several prototypes. The experiments were conducted with the same protocol to verify the effectiveness of the developed suits. Therefore, the subjects and subject numbers were different. To compare the experimental result obtained with different suits, the effectiveness was analyzed using a t-test based on the following conditions: 1) one-tailed, which can demonstrate a "significantly better" result observed when wearing the assistive suit, and 2) the "unpaired data," which was chosen because the subjects involved in the development period were different. The subject information is shown in **Table 6**.

Figures 16(a) and **(b)** show the results of the BB and PM muscles of the subjects with and without the proposed suits Prototype-1, Prototype-2, Prototype-3, and e.z.UP®. Compared with the prototype suits, e.z.UP® showed effectiveness with above 95% confidence in each phase. The results without any assistive suit indicated that the dynamic motion (phases 1 and 3) had greater values in both the BB and PM muscles. In other words, dynamic motions may easily cause injury in both the BB and PM muscles simultaneously. Comparing the BB and PM muscles at Phase 1, maximum muscle activities appeared, indicating that greater assistance is required. The simulation results in **Fig. 13** showed that the maximum assistive force can be generated at Phase 1. This finding proved that the user can be adequately assisted as needed according to their motion/posture.

For the arm assistance, the experiment of the BB muscle in **Fig. 16(a)** proved that wearing e.z.UP® can successfully reduce muscle activity. Comparing the experimental results of the BB muscle and the simulation results shown in **Fig. 13(e)**, the torque of the elbow joint can be decreased in all phases, which has the same tendency as the experimental results (**Fig. 16(a)**). Although the joint torque cannot directly reflect the actual muscle activity, the tendency of the decreased torque can be compared. In the simulation, a fixed-size human body model was considered. However, as different subjects have different body dimensions, these factors can influence the experimental results. This study discusses the experimental results by observing the tendency of the simulation results. In the simulation result of the BB muscle, the decreasing ratio (η) has the maximum assistance during Phase 1. However, the experimental results showed the maximum assistance at Phase 3, which may be caused by the friction between the belts and the fabrics. The contact pressure between the belts and the fabrics reached a maximum at Phase 1 while the user was squatting. The friction can influence the assistive force generated by the belt. Although the friction decreased the assistance of the BB muscle, the improved ratio can still reach 38% on average.

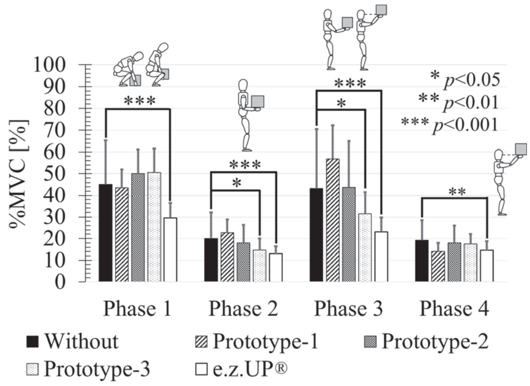
Figure 16(b) shows the results of the PM muscle. The required assistive force may differ according to the different postures. Lower-back injuries generally occur when a user lifts a load from the ground because of generating momentum. The proposed two-layer structure provides the maximum assistive force at Phase 1 due to the bending angle of the torso. The effectiveness of the PM muscle assistance showed a stable improved ratio of approximately 30% to 37%, indicating that the assistive force generated by the two-layer structure can gradually and adequately assist the user's back muscle while lifting the load. Chen [14] revealed that the arm muscle was weaker than the back muscle because of the size of the muscle group. Therefore, the arm muscle may easily encounter fatigue during a repeated motion. The change of posture can cause lower-back injuries when the localized muscle encounters fatigue. Comparing the improved ratios of the BB and PM muscles in **Figs. 16(a)** and **(b)**, the BB muscle showed greater effectiveness. This may prove that the fatigue of the localized arm muscle can be prevented, and that the injury of the lower back may be prevented further because of the greater effectiveness.

Furthermore, apart from the t-test evaluation, the %MVC ratio ($\%\mathrm{MVC}_{with}/\%\mathrm{MVC}_{without} \times 100\%$) was calculated directly to confirm the effectiveness. **Fig. 17** shows the results. In the result of Phase 3 with Prototype-1 and Phase 1 with Prototype-2, the %MVC ratio exceeded 100%. In other words, muscle activities may increase while these suits are worn. Although Prototype-3 can be effective in all phases, the compressive force of the waist belt caused discomfort while the user tightened Belt 1 and Belt 2. The results also proved that e.z.UP® achieves higher assistive effectiveness and is user-friendly.

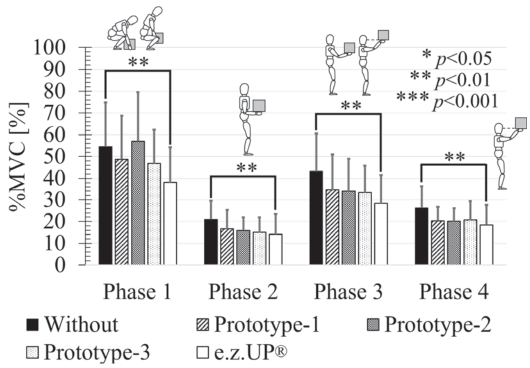
In the experiment of e.z.UP®, seven middle-aged sub-

Table 6. Subjects' information in EMG measurement with different suits.

	Without		Prototype-1 and Prototype-2	Prototype-3	e.z.UP®	
Subject	Young	Middle age	Young	Young	Young	Middle
Number	16	7	6	6	7	7
Gender	2 Females; 14 Males	All males	1 Female; 5 Males	1 Female; 5 Males	All males	
Age	33.5±15.8		22.7±0.5	23.7±1.2	40.1±17.3	
Height	172.9±6.5		172.8±6.2	175.0±9.7	173.7±6.4	
Weight	68.2±9.9		67.2±13.1	67.2±12.2	70.2±8.9	

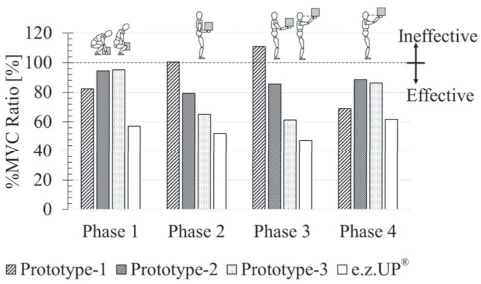


(a) BB muscle

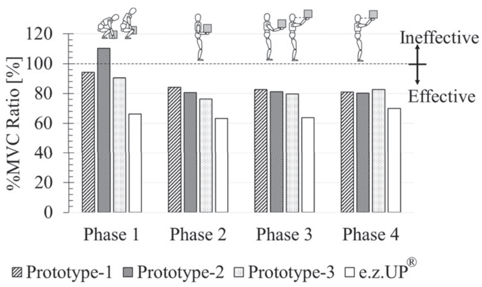


(b) PM muscle

Fig. 16. Experimental results of BB and PM muscles with all suits under a lifting motion.



(a) BB muscle



(b) PM muscle

Fig. 17. Comparisons of the %MVC ratios with all suits under a lifting motion.

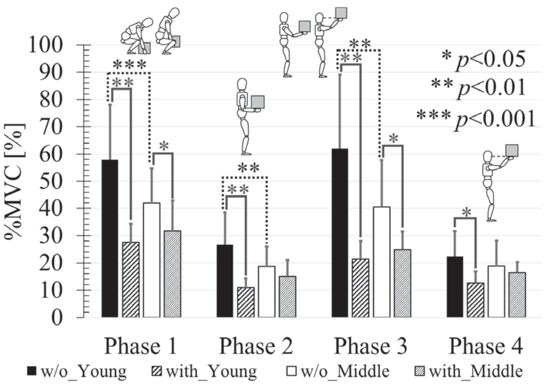
jects participated. It is interesting to observe the different lifting methods according to their habits. Hence, the BB and PM muscles were compared based on the results without wearing the suit for young and middle-aged subjects. The subject information was arranged, as shown in **Table 7**. The comparison results are shown in **Fig. 18** based on the following t-test conditions: 1) two-tailed, which can demonstrate a "significant difference," and 2) "paired data." To confirm the decreasing ratio, the t-test for young subjects with and without suits was evaluated with the following conditions: 1) one-tailed and 2) unpaired data. For the middle-aged subjects, the t-test conditions are described as follows: 1) one-tailed and 2) paired data.

The results showed evidently different habits of the young and middle-aged subjects (dash line). The young

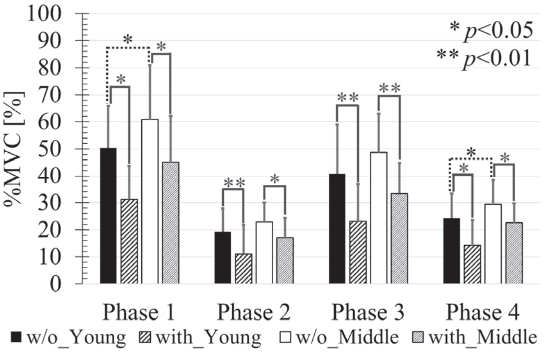
Table 7. Subjects' information in the e.z.UP® experiment.

	Without		e.z.UP®	
Subject	Young	Middle	Young	Middle
Number	16	7	7	7
Gender	2 Females; 14 Males	All males	All males	All males
Age	23.4±1.0	56.7±3.0	23.6±0.8	56.7±3.0
Height [cm]	173.9±6.9	170.6±5.4	176.9±6.1	170.6±5.4
Weight [kg]	69.7±10.9	64.7±6.9	75.7±7.2	64.7±6.9

subjects unintentionally use their arm muscle (BB) while the lifting the weight due to the greater strength of the arm muscle (**Fig. 18(a)**). On the contrary, the middle-aged subjects tend to use lower-back muscle (PM) for lifting the weight (**Fig. 18(b)**). Based on the body conditions of the target user, the assistance requirements dif-



(a) BB muscle



(b) PM muscle

Fig. 18. Experimental results of the difference of young and middle-aged subjects under a lifting motion.

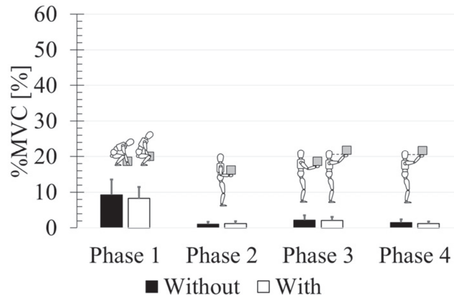
Table 8. Subjects' information in the lower-limb experiment.

	Without	e.z.UP®
Subject	Young	
Number	6	
Gender	All males	
Age	23.5±0.8	
Height [cm]	173.9±4.1	
Weight [kg]	73.7±8.1	

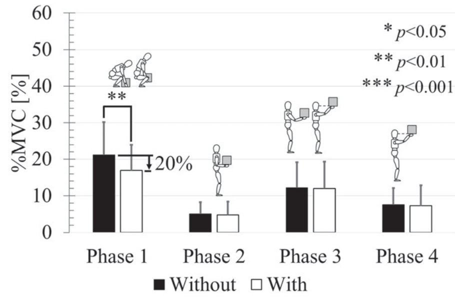
fered. Young subjects require more arm assistance, and middle-aged subjects demand higher assistance on their lower-back. The results revealed that the assistance can be provided for different target users. In other words, our proposed suit can successfully assist not only the arm muscle but also the lower-back muscles as needed. Wearing the suit may prevent injuries and hazard in their daily tasks by successfully assisting the arm muscle [14].

5.2.2. Lower-Limb Assistance

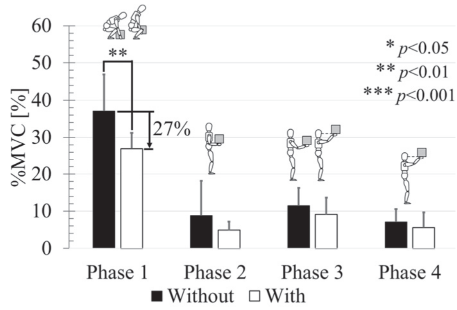
For the evaluation of lower-limb assistance, six young subjects participated in this experiment with the same lifting motion. The information of the subjects is shown in **Table 8**. The effectiveness was analyzed using a t-test based on the following considerations: 1) one-tailed,



(a) TA muscle



(b) GAS muscle



(c) SOL muscle

Fig. 19. Experimental results of lower-limb assistance with e.z.UP® under a lifting motion.

which can demonstrate a "significantly better" result observed when wearing the assistive suit, and 2) the "paired data," which was chosen because the subjects who wore and did not wear wearing e.z.UP® were the same.

The experimental results regarding the effectiveness of lower-limb assistance are shown in **Fig. 19**. The muscle activities of GAS and SOL (**Figs. 19(b)** and **(c)**) were greater than the TA muscle activity (**Fig. 19(a)**) because the experimental motion is mainly related to the foot plantar flexion motion. The maximum muscle contractions of GAS and SOL muscles appeared at Phase 1. It was the same as the simulation result of the ankle joint (**Fig. 13(a)**). The decreasing ratios (η) of the GAS and SOL muscles were 20% and 27%, respectively. As the ankle and knee joints become smaller, the required muscle contractions of GAS and SOL also become smaller. According to the experimental result of the TA muscle (**Fig. 19(a)**), the proposed suit provides adequate assistance without additional burden on the TA muscle and successfully assists lower-limb muscles (GAS and SOL muscles).

6. Conclusions

This study proposed a close-fitting assistive suit with an adjustable structure, called e.z.UP®, for the muscle assistance of manual handling workers in their daily tasks, especially for arm and back assistance. This suit was composed mainly of elastic components (i.e., rubber belts and deformable fabrics) and non-deformable components (i.e., nylon belts and non-deformation fabrics). The arm assistive belts were modified according to a previously proposed suit. It can adequately generate assistive force as needed according to the motion/posture of the user. A two-layer elastic structure was proposed to assist the user's back muscle with the non-linear characteristic, which can generate the assistive force gradually. A simulation was conducted based on the averaged human body model wearing the proposed suit to observe the belt deformation according to the user's motion and verify the feasibility of the proposed layout of the arm assistive belts. The simulation results proved that the proposed suit can adequately assist the user without additional burden. Furthermore, an experiment was conducted to confirm the feasibility of not only the arm assistive belt but also the two-layer elastic structure. The results were also compared with the experimental result of our previously proposed suits with six young subjects. The results proved that the proposed suit can adequately and successfully decrease the muscle activities by 34% to 47% with the arm assistance by our proposed layout of arm assistive belts. The effectiveness of back muscle assistance can successfully reach a value above 30%. The results for the confirmation of lower-limb assistance also proved that the decreasing ratio of not only the upper-limb muscles but also the lower-limb muscles could be up to 20% with the use of e.z.UP®.

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