Development of a new compact and light velocity-based mechanical safety device for a rehabilitation assist suit

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Abstract
Safety is an important requirement in rehabilitation assist suits. We have developed a velocity-based mechanical safety device (VBMSD) for an assist suit to aid in the flexion and extension of a patient’s knee joint. The VBMSD is attached to the assist suit. The VBMSD stops the suit’s motor when the angular velocity of the knee joint matches or exceeds a preset threshold level. This level is called the “detection velocity level (DVL)” and it is adjustable based on the specification of each patient’s gait training. Since the VBMSD is composed only of passive mechanical elements such as a rotary damper, it works even when the suit’s computer has stopped working. In view that portability is equally important as safety in wearable assist devices, the size and the weight of the VBMSD must be reduced for practical use. This paper presents the design and development of a new compact and light VBMSD. First, we describe the problems in the previous VBMSD. Second, we present the requirements and design specifications in the new VBMSD. The requirements and design specifications in the new VBMSD’s size are determined by considering International Organization for Standardization (ISO) 13482 and Advanced Industrial Science and Technology (AIST) human body dimensions data. Third, we propose the structure and the mechanism of the new VBMSD. Fourth, we explain the design process of the new VBMSD. In the design process, the frequency response and the transient response of the new VBMSD are also considered. Fifth, experimental results to check whether the new VBMSD achieves the necessary function are presented. Lastly, the possibility of installing the new VBMSD to an ankle joint assist suit and a wrist joint assist suit is discussed using AIST human body dimensions data, etc.

Keywords: Robot, Design, Mechanism, Exoskeletal robot, Mechanical safety device, Frequency response analysis, Transient response analysis

1. Introduction
Recently, the development of wearable rehabilitation assist suits is receiving increasing attention (Bernhardt et al., 2005) (Kawamoto et al., 2014) (Banala et al., 2007) (Luu et al., 2014). Safety of patients is of critical importance in assist suits.

We can improve the safety by using computer control techniques (Bae et al., 2011). Assist suits, however, will move unexpectedly and be hazardous to patients when the computer has not operated correctly. Hence, assist suits equipped with hardware-based safety devices are desired to secure the safety of patients even when the computer has stopped working.

Generally, in hardware-based safety devices of assist suits, emergency switches and/or joint limiters are used (Huo et al., 2018) (Feng et al., 2016) (Kong and Jeon, 2005). Emergency switches are able to stop unexpected motions of the
assist suits. In an emergency, however, patients and/or caregivers might run into difficulties pushing the emergency switch. Joint limiters can protect patient’s joints from hyperextension. The assist suit, however, might move patient’s joints at unintended high angular velocities in advance of joint limiters protecting from the exertion, which may cause the patient to get injured or feel pain.

To address these problems, we have proposed and developed a knee joint assist suit equipped with a velocity-based mechanical safety device (VBMSD) (Sugiyama et al., 2017). The assist suit was designed for conducting the gait training of patients who have difficulty moving their knee joints (e.g., patients with neurological diseases such as stroke or patients with peripheral neuropathy) using a treadmill and a lift device shown in Fig. 1. The VBMSD switches off the suit’s motor when the knee joint angular velocity produced by the motor matches or exceeds a preset threshold level. This level is called the “detection velocity level (DVL)” and it is adjustable based on the specification of each patient’s gait training. Additionally, since the VBMSD has only passive mechanical elements such as a rotary damper, it works even when the suit’s computer has stopped working. Furthermore, we proposed a method to theoretically examine whether the VBMSD will resonate with a patient’s walking cycle (0-1 Hz (Kirsten, 2003)) by using the frequency response analysis (Kai et al., 2018). Then, the effectiveness of the method was proven by experiments because the VBMSD may malfunction when it resonates with the cycle. Moreover, we proposed a method to theoretically check the response speed of the VBMSD to a rapidly rising velocity from the transient response of the VBMSD (Kaneda et al., 2019). Then, the effectiveness of the method was also verified by experiments.

However, in view that portability is equally important as safety in wearable assist devices, the size and the weight of the VBMSD must be reduced for practical use.

This paper describes the design and development of a new compact and light VBMSD (new VBMSD). In this paper, first, we describe the problems in the previous VBMSD. Second, we present the requirements and design specifications in the new VBMSD. The requirements and design specifications in the new VBMSD’s size are determined by considering International Organization for Standardization (ISO) 13482 Robots and robotic devices - safety requirements for personal care robots (International Organization for Standardization, 2014) and Advanced Industrial Science and Technology (AIST) human body dimensions data (National Institute of Advanced Industrial Science and Technology, 2020). Third, we introduce the structure and the mechanism of the new VBMSD. Fourth, we explain the design process of the new VBMSD. In the design process, the frequency response and the transient response of the new VBMSD are also considered. Fifth, experimental results to check whether the new VBMSD achieves the necessary function are presented. Lastly, the possibility of installing the new VBMSD to an ankle joint assist suit and a wrist joint assist suit is discussed using AIST human body dimensions data, etc.

2. Knee joint assist suit with the new VBMSD

As shown in Fig. 2, there is a risk that a patient’s leg may be moved by the assist suit at unintended high velocities when the assist suit’s computer has not operated correctly. By being moved at unintended high velocities, the patient might get injured and feel pain or scared. In order to reduce this risk, we have proposed and developed a velocity-based mechanical safety device (VBMSD) and a knee joint assist suit equipped with it (see Fig. 3). However, this VBMSD is too large and heavy, then the size and the weight of the VBMSD must be reduced for practical use. Hence, we designed and developed a new more compact and lighter VBMSD (new VBMSD) in this study.
Figure 4 represents the knee joint assist suit equipped with the new VBMSD. The assist suit is affixed to a patient’s leg with braces (a calf brace and two thigh braces) and aids in the flexion and extension of the patient’s knee joint. The motor of the suit is affixed to Frames 1 and 2 via Bracket 1. Then, the torque of the motor is transmitted to the patient’s knee joint via a gearhead, a coupling, Shaft 1, a torque limiter, Shaft 2, a torsion spring, Shaft 3, Bevel Gears 1 and 2, Shaft 4, Frame 3, and the calf brace. Gear 2 in the new VBMSD is rotated by Shaft 4 via Gear 1. Also, the motor’s rotational angle is measured by Encoder 1. Likewise, Shaft 4’s rotational angle is measured by Encoder 2 via Gears 1, 2, and 3.

The new VBMSD switches off the motor when Shaft 4’s angular velocity matches or exceeds a preset threshold level - the “detection velocity level (DVL).” When Shaft 4’s torque exceeds a preset threshold level, the torque transmission is cut off by the torque limiter. The torsion spring is used (i) to play the role of an energy buffer between the motor and the patient’s knee joint and (ii) to measure the torque produced by the suit by using Encoders 1 and 2 (Kong et al., 2012).

Fig. 2 Problem in the case of computer failure. When the assist suit’s computer has stopped working, the assist suit might move a patient’s leg at unexpected high velocities.

Fig. 3 Knee joint assist suit with the previous VBMSD. The previous VBMSD has large parts such as two large switches.

Fig. 4 Structure of the assist suit with the new VBMSD. The assist suit assists a patient's knee joint. Shaft 4’s angular velocity is transmitted to Gear 2 in the new VBMSD via Gear 1.
3. Problems in the previous VBMSD

3.1 Structure and mechanism of the previous version

Figure 5 illustrates the structure of the previous version. The previous VBMSD is affixed to the knee joint assist suit shown in Fig. 4 in place of the new VBMSD. Gear 2 is rotated by Shaft 4 via Gear 1. Gear 2 is combined with a rotary damper which is supported by Bracket 4 via a bearing. A bar is joined to the output shaft of the rotary damper. Two tension springs are affixed to the bar. Also, the tension springs’ ends are affixed to Bracket 4 by two pins. Furthermore, Bracket 4 is affixed with two switches, and then Bracket 4 is affixed to Frame 2.

Figure 6 represents the mechanism of the previous VBMSD. While Gear 2 is rotated by Shaft 4, the damping torque produced by the rotary damper and the spring torque produced by the tension springs act on the bar. The bar is rotated by the torque difference between the damping and spring torques and switches off the motor if Shaft 4’s velocity matches or exceeds the DVL. Also, the bar can switch off the motor in the counter direction. In addition, the DVL is adjustable by changing the switches’ attachment positions.

3.2 Problems in the previous version

Since we used two tension springs in the previous version, the length of the two tension springs was required in the previous version’s width as shown in Fig. 7. Moreover, we used large parts in the previous version in order to easily replace them and to easily measure their movements (e.g., a large bar, two large switches).

We present the new VBMSD designed and developed to solve these problems in the next section.
4. New VBMSD designed and developed in this study

In this study, as one step for practical use, we designed and developed the new VBMSD satisfying the following requirements and design specifications.

4.1 Requirements and design specifications in the new VBMSD

In ISO 13482, “Intended use case scenarios to perform intended tasks by the personal care robot shall be considered in the design of the overall shape of the robot, and of its external parts, to avoid the potential for accidents that could cause, for example, crushing, cutting, or severing injuries.” is written (International Organization for Standardization, 2014). If devices attached to an assist suit outwardly protrude from a human body, they might cause cutting injuries, etc. Therefore, the devices should not protrude from the section of the body where they are attached.

The mean and standard deviation of the knee depths (see Fig. 8) of elderly females over 60 in Japan are 109.1 mm and 7.28 mm (National Institute of Advanced Industrial Science and Technology, 2020a). This mean value is smaller than the mean values of elderly males or young adults. Also, the standard deviation is larger than the standard deviations of elderly males or young adults. Therefore, if the width of the new VBMSD is smaller than 87.2 mm (That is, Mean - 3 × Standard Deviation), the new VBMSD will not protrude from the knee depths of approximately all adults.

Table 1 shows the requirements and design specifications of the new VBMSD. The target size of the new VBMSD’s width was set smaller than 87.2 mm (C1). The goal for the length of the new VBMSD was set smaller than 72 mm, which is Gear 2’s diameter in the previous version, in order for the new VBMSD not to protrude from the knee

| Table 1 Requirements and design specifications in the new VBMSD. |
|---------------------------------------------------------------|
| **C1: Width** | The width is smaller than 87.2 mm in order not to protrude from the knee depths of approximately all adults. |
| **C2: Length** | The length is smaller than 72 mm, which is Gear 2’s diameter in the previous version, in order not to protrude from the knee joint. |
| **C3: Depth** | The depth is smaller than 55 mm, which is the previous version’s depth. |
| **C4: Weight** | The target of the weight was set lighter than 270 g, which is the previous version’s weight. |
| **C5: DVL** | The DVL is adjustable up to the knee joint angular velocity of 5.5 rad/s. |
| **C6: Frequency response** | The new VBMSD does not resonate with the walking cycle (0-1 Hz). |
| **C7: Transient response** | The time delay until the bar has switched off the motor after Shaft 4’s velocity has exceeded the DVL is approximately equal to or less than the previous version’s time delay. |
joint (C2). Furthermore, the target of the depth was set smaller than 55 mm, which is the previous version’s depth (C3). The target of the weight was set lighter than 270 g, which is the previous version’s weight (C4). Additionally, it is said that the knee joint angular velocity of approximately 6 rad/s is needed in healthy adults’ walking. Therefore, the target for the DVL was set adjustable up to the knee joint angular velocity of approximately 5.5 rad/s considering that the new VBMSD is used in the patients’ gait training (Matsunaga, 2008) (C5). In C5, Gear 2’s velocity is important in the VBMSD. In the previous VBMSD, the DVL at Gear 2 is adjustable up to approximately 5 rad/s. On the other hand, since the DVL at Gear 2 is adjustable up to approximately 5.5 rad/s in the new VBMSD satisfying this specification, the DVL’s range is larger than the previous version. Moreover, the goal for the frequency response was set to the same as the previous version (C6) and the goal for the transient response was set approximately equal to or better than the previous version (C7).

In the next section, we explain the structure and the mechanism of the new VBMSD for satisfying the requirements and design specifications.

4.2 Structure and mechanism of the new VBMSD

Figure 9 illustrates the structure of the new version. Two torsion springs were used in the new version in place of the two tension springs. Due to this, the length of the two tension springs was not required in the width. Moreover, we selected the smallest and lightest parts possible such as the switches. In addition, we designed some components such as the bar and made them by using a 3D printer (Zortax M200, Zortax S. A.).

As shown in Fig. 9, Shaft 4 rotates the rotary damper via Gears 1 and 2. The rotary damper is supported by Bracket 4 via a bearing. The bar in the new VBMSD is joined to the rotary damper’s output shaft. Two torsion springs are attached to the bar. The torsion springs’ ends are attached to Bracket 4. Two switches are set in switch brackets. Each switch bracket can slide along a bolt and be fixed by two nuts. By changing the attachment positions of the switch brackets, the DVL is adjustable. In order to raise the spring torque and to use the torsion springs within the allowable deflection angle (Fig. 10), two torsion springs were used in this study.
The mechanism of the new VBMSD is shown in Fig. 11. If the bar’s center of gravity equals the output shaft axis of the rotary damper, then the gravitational torque acting on the bar is zero. Also, if the influence of the friction has no significance, the bar’s motion equation is represented by Eq. (1).

\[
I\ddot{\theta} + k(\gamma + \theta) - k(\gamma - \theta) = c(v - \dot{\theta})
\]  

(1)

where \( \theta \) is the bar’s rotational angle, \( I \) is the moment of inertia of the bar, \( v \) is Gear 2’s angular velocity, \( c \) is the damping coefficient of the rotary damper, \( \gamma \) is the initial angular displacement of the torsion spring from the unloaded position (We set \( \gamma = \beta / 2 = \text{const.} \), where \( \beta \) is the allowable deflection angle of the torsion spring.), and \( k \) is the spring constant of the torsion spring.

The bar’s motion equation is represented by Eq. (2) if \( I\ddot{\theta} \) and \( c\dot{\theta} \) are minute enough in Eq. (1).

\[
2k\theta = cv
\]  

(2)

From Eq. (2), the DVL at Shaft 4 is expressed by Eq. (3) (see Fig. 12).

\[
v_D = \chi(2k\theta_p + \tau_p) / c
\]  

(3)

where \( \theta_p \) is the bar’s angle required for switching off the motor, \( \chi \) is the gear ratio of Gear 1 to Gear 2, and \( \tau_p \) is the torque required for pushing the switch. By adjusting the attachment positions of the switch brackets using Eq. (3), we can approximately set the DVL.

4.3 Design process of the new VBMSD

Figure 13 shows the design process of the new VBMSD. According to the design process, we designed the new VBMSD. We redesigned the new VBMSD from the beginning if the requirements and design specifications were not satisfied. Moreover, we reduced the size and weight of the new VBMSD as much as possible. Each process is as
follows:

(i) Selection of a rotary damper
Firstly, we selected a rotary damper in order to design the new VBMSD. In this paper, we selected TD62W-1-1500 considering the size, the weight, the durability, the revolution speed characteristic, and the characteristic of temperature.

(ii) Selection of torsion springs and switches
In order to satisfy the requirements and design specifications in the new VBMSD, we selected the smallest and lightest switch and torsion spring possible. The spring constant of the torsion spring was determined as follows:
As shown in Fig. 14, the force required for pushing the switch, $F_p$, is expressed by $F_p = \tau_p / L$, where $L$ is the length from the output shaft axis of the rotary damper to the bar’s tip.
However, when the bar rotates by $\theta_p$, strictly speaking, the switch is pushed by $F_p \cos \theta_p$. Therefore, $\theta_p$ should be set in a range satisfying $\cos \theta_p \approx 1$. We set the maximum angle to 8 deg because $\cos 8^\circ \approx 1$. Then we selected the torsion spring with the spring constant to satisfy the DVL = approximately 5.5 rad/s when $\theta_p = 8$ deg.

(iii) Design of the bar
In considering the size and weight of the new VBMSD, the length $L$ of the bar is required to be as short as possible. However, if $L$ is too short, then the range of the switch’s attachment position $\Delta x = L \sin \theta_p$ (see Fig. 14) is also small and we have difficulty setting the switch to the desired position. Hence, we set $L = 18$ mm considering the setting of the switch.
Moreover, it is important that the bar’s center of gravity coincides with the rotary damper’s shaft axis in the new VBMSD. We designed the bar while checking whether the bar’s center of gravity coincides with the rotary damper’s shaft axis by using the software, Inventor by Autodesk inc. In the design, we also considered the strength and the deflection of the bar.

(iv) Selection and design of the other parts
We selected and designed the other parts considering the sizes, the weights, and the strengths of them.

(v) Frequency response analysis and transient response analysis of the new VBMSD
This process is demonstrated in Section 5.

4.4 New VBMSD designed and developed in this paper
Table 2 represents the parameter values of the new VBMSD which we developed based on the above design. Figures 15 and 16 show the contrast between the previous and the new VBMSDs. While the previous version’s height, width, and depth are 150 mm, 140 mm, and 55 mm, the newly developed version’s height, width, and depth are 52 mm, 50 mm, and 40 mm. Moreover, the previous version’s weight and the new version’s weight are approximately
270 g and 59 g, respectively. The new version’s weight is approximately the weight of a medium-sized chicken egg (Ministry of Agriculture, Forestry and Fisheries of Japan, 2020). Therefore, we can conclude that the new version is undoubtedly smaller and lighter than the previous version. As shown in section 5, the new version has approximately the same performance as the previous version in the frequency response and the transient response. Therefore, we can conclude that the new VBMSD satisfies C1 – C7 requirements and design specifications.

In this study, we used Gear 1 having the same number of teeth as Gear 2. Therefore, in the following, $\chi = 1$, that is, Gear 2’s velocity is equal to Shaft 4’s velocity.

### 5. Frequency response analysis and transient response analysis of the new VBMSD

Since the new VBMSD is composed only of passive mechanical elements such as springs, it has the risk that it might resonate with a patient’s walking cycle (0-1Hz), and then stop the motor when Shaft 4’s velocity is under the DVL. Also, the time delay until the bar has switched off the motor after Shaft 4’s velocity has exceeded the DVL is important. If the time delay is excessive, a patient’s leg might be moved by the suit at unexpected high velocities.

In this section, we check whether the new VBMSD satisfies C6 and C7 by using the frequency analysis and the transient response analysis.

Assuming that $I\ddot{\theta}$ and $c\dot{\theta}$ are minute enough in Eq. (1), we obtained Eq. (3). We use Eq. (3) in order to set the DVL because we can easily set it by using Eq. (3). However, $I\ddot{\theta}$ and $c\dot{\theta}$ are not strictly zero. Therefore, we analyze considering $I\ddot{\theta}$ and $c\dot{\theta}$ in this section. We obtain Eq. (4) from Eq. (1).

$$I\ddot{\theta} + 2k\theta = c(\nu - \dot{\theta})$$ (4)
5.1 Frequency response analysis of the new VBMSD

From Eq. (4), we obtain Eq. (5).

\[ \Theta(s) = G(s)V(s) \]  

where \( G(s) = c / (Is^2 + cs + 2k) \), \( \Theta(s) \) is the Laplace transform of \( \theta \), and \( V(s) \) is the Laplace transform of \( v \). The bar’s frequency response for Gear 2’s velocity \( v(t) = A \sin \omega t \) is expressed by

\[ \theta(t) = |G(i\omega)|A \sin(\omega t + \angle G(i\omega)) \]  

where \( \omega \) is the frequency of \( v(t) \), \( A \) is the amplitude of \( v(t) \), \( \angle G(i\omega) \) is the phase difference between \( v(t) \) and \( \theta(t) \), and \( |G(i\omega)| \) is the magnitude of \( G(i\omega) \). \[ |G(i\omega)| \] is represented by

\[ |G(i\omega)| = c / \sqrt{(2k - I\omega^2)^2 + (c\omega)^2} \]  

The resonance frequency \( \omega_R \) which maximizes \( |G(i\omega)| \) is represented by

\[ \omega_R = \sqrt{R} \omega_N \]  

where \( R = 1 - c^2 / (4kI) \) and \( \omega_N \) is the natural frequency (i.e., \( \omega_N = \sqrt{2k/I} \)).

If \( R < 0 \), then the bar does not resonate with any walking cycle (Yoshida, 2003). Since \( R \approx -1424 < 0 \) in the new VBMSD, we determined that the new version does not resonate with any walking cycle.

Moreover, we obtained the frequency response from Gear 2’s velocity to the bar’s angle in the new version by using Table 2’s parameter values and Eq. (5). Figure 17 shows the frequency response. Figure 17(a) reveals the magnitude response and Fig. 17(b) reveals the phase response.

Figure 17(a) indicates that \( |G(i\omega)| \) is approximately constant in 0-1 Hz (i.e., 0-6.28 rad/s). Hence, we

![Fig. 17 Frequency response of the new VBMSD. (a) Gain response (i.e., Magnitude response), (b) Phase response.](image-url)
concluded that the new version will not resonate with the walking cycle of 0-1 Hz. Additionally, Fig. 17(b) indicates that \( \angle G(i\omega) \) is approximately zero in 0-1 Hz. Since \( \lim_{t \to 0} |G(i\omega)| = \sqrt{c/2k} \) from Eq. (7), Eq. (6) nearly equals Eq. (2) in the walking cycle of 0-1 Hz. Therefore, we can expect the bar to promptly respond to Gear 2’s velocity based on Eq. (2) in the walking cycle.

From the above statements, we judged that the new VBMSD with Table 2’s parameter values satisfied C6.

5.2 Transient response analysis of the new VBMSD

In this section, we analyze the bar’s response for a rapidly increasing Gear 2’s velocity

\[ v = at \]  

where \( a \) is the angular acceleration of Gear 2.

As shown in Fig. 18, the bar’s response for Eq. (9) is obtained from three phases: (i) before contacting the switch lever (i.e., \( \theta(t) < \theta_0 \)), (ii) after contacting the switch lever and before moving the switch lever (i.e., \( \theta(t) = \theta_0 \)), and (iii) during moving the switch lever (i.e., \( \theta(t) > \theta_0 \)). \( \theta_0 \) is the bar’s rotational angle where the bar has contacted the lever.

(i) Before contacting the switch lever (i.e., \( \theta(t) < \theta_0 \)):

In this case, the bar’s motion equation is expressed by Eq. (4). By taking the Laplace transform of Eqs. (4) and (9) and then eliminating \( V(s) \), we obtain Eq. (10).

\[
I(s^2 \Theta(s) - s\theta(0) - \dot\theta(0)) + 2k\Theta(s) = c(a \frac{1}{s^2} - (s\Theta(s) - \theta(0)))
\]  

If \( \theta(0) \approx 0 \) and \( \dot\theta(0) \approx 0 \) (that is, the bar’s angle and the velocity are minute enough at the instance of the assist suit’s computer breaking down), then we obtain Eq. (11) from Eq. (10).

\[
\dot\theta(t) = \frac{ac}{I} \left( \frac{1}{U_1 U_2^2} I + \frac{1}{U_1^2 (U_1 - U_2)} + \frac{1}{U_2^2 (U_2 - U_1)} \right) e^{\frac{a}{2k} t}
\]

where \( U_1 = -(c + \sqrt{c^2 - 8kI})/(2I) \) and \( U_2 = -(c - \sqrt{c^2 - 8kI})/(2I) \).

(ii) After contacting the switch lever and before moving the switch lever (i.e., \( \theta(t) = \theta_0 \)):

In this case, the bar can not move until the damping torque acting on the bar exceeds the torque required to move the switch lever \( 2k\theta_0 + \tau_a \) (\( \tau_a \) is the initial torque of the switch). Therefore, the bar’s response is expressed by

\[
\theta(t) = \theta_0
\]

Let the time when the bar starts moving be \( t_0 \).

(iii) During moving the switch lever (i.e., \( \theta(t) > \theta_0 \)):

Let us consider a new time \( t' = t - t_0 \) and an angle \( \psi(t') = \theta - \theta_0 \) as shown in Fig. 18 (iii). Then the bar’s
motion equation is expressed by Eq. (13).

\[ I\ddot{\psi} + 2k(\psi + \theta_0) + r_a k_v \psi = c(\nu - \psi) \] (13)

where \( k_a \) is the spring constant of the switch. From Eq. (9), Gear 2’s velocity \( \nu \) is expressed by Eq. (14).

\[ \nu = a(t^2 + t_0) \] (14)

By taking the Laplace transform of Eqs. (13) and (14) and then eliminating \( I(s) \), we obtain Eq. (15).

\[ I(s^2\psi(s) - s\psi(0) - \psi(0)) + 2k(\psi(s) + \frac{\theta_0}{s}) + \frac{r_a}{s} \psi(s) + k_v \psi(s) = c\left(\frac{a}{s^2} + \frac{at_0}{s} - s(\psi(s) - \psi(0))\right) \] (15)

where \( \psi(s) \) is the Laplace transform of \( \psi(t) \). Eq. (16) is obtained from Eq. (15), \( \psi(0) = 0 \), and \( \psi(0) = 0 \).

\[ \psi(t) = Z_1e^{W_1t} + Z_2e^{W_2t} + Z_3t + Z_4 \] (16)

where \( W_1 = \left(-c + \sqrt{c^2 - 4(2k + k_a)t}\right)/\left(2I\right) \), \( W_2 = \left(-c - \sqrt{c^2 - 4(2k + k_a)t}\right)/\left(2I\right) \), \( Z_1 = \frac{ca - 2k\theta_0 - r_a}{I(W_1 - W_2)W_1^2} \), \( Z_2 = \frac{ca - 2k\theta_0 - r_a}{I(W_2 - W_1)W_2^2} \), \( Z_3 = \frac{ca}{IW_1W_2} \), and \( Z_4 = \frac{ca(W_1 + W_2)}{IW_1^2W_2^2} + \frac{ca - 2k\theta_0 - r_a}{IW_2} \). Hence, the bar’s response is expressed by Eq. (17).

\[ \theta(t) = Z_1e^{W_1(t - t_0)} + Z_2e^{W_2(t - t_0)} + Z_3(t - t_0) + Z_4 + \theta_0 \] (17)

We simulated how promptly the bar responds to a rapidly increasing velocity \( \nu = 23t \) (i.e., \( a = 23 \text{ rad/s}^2 \): This is the maximum acceleration which the developed assist suit can output at Gear 2.) by using Table 2’s parameter values and Eqs. (11), (12), and (17).

Figure 19 shows the simulation results for (i) DVL = 1.1 rad/s, (ii) DVL = 1.9 rad/s, and (iii) DVL = 2.6 rad/s. \( \theta_p \) for each DVL was obtained by using Eq. (3) and then each \( \theta_0 \) is obtained from \( \theta_0 = \theta_p - 1 \) deg. The newly developed VBMSD has \( \theta_p = \theta_0 = 1 \) deg. The horizontal axis of these figures represents time (in seconds) and the two vertical axes represent Gear 2’s angular velocity and the bar’s angle. In each figure, Gear 2’s velocity is represented by a red line until reaching the DVL and the bar’s response is represented by a blue line until reaching the angle required to switch off (i.e., \( \theta_p \)). From Fig. 19, we can find that the time delay between the instant the velocity exceeded the DVL and the instant the motor switched off is approximately 0.023 seconds. This time delay is approximately the same as the previous version’s value (The previous version’s time delay is approximately 0.022 seconds (Kaneda et al., 2019)). It was concluded that we could have designed the new version which has approximately the same performance as the previous version, and is lighter and smaller than the previous version. Therefore, we judged that the new VBMSD with Table 2’s parameter values satisfied C7.

From the simulation results, we can expect that Gear 2’s velocity will increase by approximately 0.53 rad/s (=23 × 0.023 seconds) after Gear 2’s velocity exceeds the DVL when the motor keeps moving at the maximum acceleration.
6. Experiment

In this section, we present experimental results to check whether the new VBMSD designed and developed in this study achieves the necessary function.

6.1 Experimental method

Figure 20 shows the experimental setup. We set up the assist suit with an LED light to detect the time when the motor was turned off by the bar. The LED light is turned on when the motor is turned off. Furthermore, for safety, Frame 3 was removed. After that, two markers were affixed to Gear 2 and then Gear 2’s angular velocity was measured by using a high speed camera system (k7-USB, KATO KOUKEN Corporation) while raising the angular velocity of the assist suit’s motor. We experimented by using the DVLs of (i) 1.1 rad/s, (ii) 1.9 rad/s, and (iii) 2.6 rad/s. We conducted thirty trials for each DVL. The sampling frequency of the high speed camera system was 200 Hz.

6.2 Results and Discussion

Figure 21 shows typical experimental results for the DVLs of 1.1 rad/s, 1.9 rad/s, and 2.6 rad/s. The red line represents Gear 2’s velocity and the blue line represents the time when the motor had been turned off by the bar. All experimental results indicated that Gear 2’s velocity (i.e., Shaft 4’s velocity) was approximately the same as the DVL when the motor had been turned off by the bar, after which Gear 2’s velocity went down to zero, as shown in Fig. 21.

Table 3 shows the mean and standard deviation of Gear 2’s velocities which were measured when the motor had been

| Detection velocity level [rad/s] | Mean [rad/s] | Standard deviation [rad/s] |
|-------------------------------|-------------|---------------------------|
| 1.1                           | 1.3         | 0.2                       |
| 1.9                           | 2.1         | 0.2                       |
| 2.6                           | 2.8         | 0.2                       |

Fig. 21 Experimental results. The red line represents Gear 2’s velocity and the blue line represents the time when the motor had been turned off by the bar.
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From the above statement, we considered that the bar of the new VBMSD promptly reacted to Gear 2’s velocity and had stopped the motor when Gear 2’s velocity (i.e., Shaft 4’s velocity) was approximately the same as the DVL. Therefore, we concluded that the new VBMSD achieved the necessary function. The differences between the DVLs and the experimental values are due to the attachment position errors of the switches, the damping torque errors of the rotary damper, the spring torque errors of thetorsion springs, the time delay described in section 5.2, the effect of friction, and several other factors. Especially, we can consider that an increase of Gear 2’s velocity due to the time delay influenced the experimental results relatively significantly because we can find the differences of 0.2 rad/s between the DVL and the mean value for all cases from Table 3. In the future, we would like to develop a new VBMSD where the time delay is shorter. Moreover, although we designed the new VBMSD considering setting the switches, we had some difficulties setting the switches due to the downsizing. Hence, we can consider that the attachment position errors of the switches also influenced the experimental results relatively significantly. In the future, we will design a new VBMSD where the switches can be set more easily. In addition, we will try to reduce the other factors. In order to improve these factors efficiently, we consider that the design flow shown in Fig. 13 should also be improved. As shown in Fig. 13, since we focused on reducing the size and weight of the new VBMSD in this paper, we used C1-C7 requirements and design specifications as the conditions which the new VBMSD should satisfy. That is, we reduced the size and weight of the new VBMSD satisfying C1-C7. Furthermore, reducing the size and weight was conducted qualitatively. In order to quantitatively optimize the new VBMSD considering not only the size and weight, but also the time delay, the ease of the setting of the switch, etc., we believe that an evaluation index considering the weighting factors of them should be used (Kai, 2011) (Chiu, 1988). In the future, we will develop the evaluation index and quantitatively optimize the new VBMSD by using the index.

Additionally, from Fig. 21, we can find that Gear 2 rotated slowly and stopped after the motor had been turned off. This is because the assist suit has high backdrivability (Kai et al., 2018) and then can move by inertia after the motor has been turned off. From this result, we can expect that the patient’s foot may collide with the treadmill. However, if this new VBMSD is not used, then the motor will not be turned off and the patient’s foot may collide with the treadmill at high velocities. Therefore, we consider that the new VBMSD should be used in order to improve the assist suit’s safety. In addition, in order to prevent the patient from falling down, the lift device should also be used as shown in Fig. 1. According to AIST Human Body Dimensions Data (National Institute of Advanced Industrial Science and Technology, 2020b), the mean and standard deviation of the minimum lower leg depths (see Fig. 22) of elderly females over 60 in Japan are 69.3 mm and 4.55 mm, and then if the width of the new VBMSD is smaller than 55 mm, the new VBMSD will not protrude from the minimum lower leg depths of approximately all adults. Therefore, we can expect that the new VBMSD developed in this paper will be installed to a foot joint assist suit without protruding from the minimum lower leg depths. Furthermore, according to AIST Hand Dimensions Data (National Institute of Advanced Industrial Science and Technology, 2020c), the mean and standard deviation of the wrist breadths (see Fig. 23) of Japanese males (18 – 64 years) are 58.1 mm and 2.9 mm, and those of Japanese females (18 – 64 years) are 51.3 mm and 2.4 mm. Therefore, we can consider that the new VBMSD developed in this paper will not protrude from the wrist breadths of 97.8 % of Japanese males and of 50 % of Japanese females. Therefore, we can also expect that the new VBMSD will be installed to a wrist joint assist suit without protruding from the wrist breadths of many people. As
shown above, since the new VBMSD using the torsion spring whose effectiveness was confirmed by experiments has high portability, we can expect it will be used in many rehabilitation assist suits.

7. Conclusion

In this paper, the design and development of a new compact and light velocity-based mechanical safety device (new VBMSD) for a rehabilitation assist suit was described in order to put it to practical use. First, the problems in the previous VBMSD were described. Second, the requirements and design specifications in the new VBMSD were presented. Third, the structure and the mechanism of the new VBMSD using torsion springs were proposed. Fourth, the design process of the new VBMSD was explained. In the design process, the frequency response and the transient response of the new VBMSD were also considered. Fifth, experimental results to check whether the new VBMSD achieved the necessary function were presented. Lastly, the possibility of installing the new VBMSD to an ankle joint assist suit and a wrist joint assist suit was discussed using AIST human body dimensions data, etc.

In the future, various kinds of experiments by using the new VBMSD (e.g., experiments for the durability) will be conducted. Furthermore, experiments with actual human subjects will be conducted in order to prove the capability of the new VBMSD. Additionally, installing the new VBMSD to not only rehabilitation assist suits but also to various kinds of robots (e.g., service robots, industrial robots, etc.) will be considered.

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