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Regression Equation between Required Force and Lumbar Load of Caregiver in Supporting Standing-up Motion via Computational Musculoskeletal Simulation

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ABSTRACT

Caregivers experience low back pain because of patient handling such as supporting standing-up. The lumbar load of a caregiver depends on the required force for patient handling motions. If the relationship between the required force and the lumbar load is quantitatively clarified, it may be useful for preventing low back pain in caregivers. In this study, we investigated the quantitative relationships between the required force and lumbar loads such as vertebral stress and muscle activity in supporting standing-up by computational musculoskeletal simulation. First, a musculoskeletal model of a caregiver was prepared, and then the model performed simulated supporting standing-up motions. The vertical load used as the required

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force was placed on the upper limb of the model. The compressive/shear stress of the vertebral (L4–L5) and muscle activities of spinae erector muscle group were recorded as the lumbar load. The results showed that there are highly significant correlations between the required force ($r > 0.9$, $p < 0.01$). In addition, regression equations for predicting each lumbar load by the required force with highly determination coefficients ($R^2 > 0.9$) were obtained from these relationships. Furthermore, we found that when the required force was more than 120 N, the compression stresses of the vertebral exceeded injury threshold (3400 N) by the regression equation. These regression equations contribute to quantitatively consider lumbar loads of caregiver during patient handling based on injury thresholds and the required force.

Keywords: Caregiver, lumbar load, musculoskeletal simulation, regression equation, required force, supporting standing-up

INTRODUCTION

Many caregivers experience low back pain because of frequent patient handling, such as transfer and supporting standing-up (Holtermann et al., 2013). Patient handling is considered to be the cause of low back pain because it involves heavy lifting, bending, and twisting (Schibye et al., 2003). There are assistive devices that reduce lumbar load during patient handlings, such as the sliding sheet and lifting robot (Iwakiri et al., 2016). However, these devices are not used in several facilities because there are limitations in time efficiency, cost, and workspace (Iwakiri et al., 2016). Therefore, it is necessary to assess the risk of low back pain due to patient handling without an assistive device.

Some studies have reported strategies for reducing the lumbar load (Ibrahim & Elsaay, 2015; Itami et al., 2010; Karahan & Bayraktar, 2004; Schibye et al., 2003). Schibye et al. (2003) reported that lumbar load during several patient handlings was reduced by pulling instead of lifting procedures (Schibye et al., 2003). Karahan and Bayraktar (2004) found that body mechanics theory was useful for reducing lumbar load during patient handling. The body mechanics theory provides suitable movements during common activities such as lifting and helps to prevent low back pain (Ibrahim & Elsaay, 2015; Itami et al., 2010; Karahan & Bayraktar, 2004). Furthermore, there is a wearable device that can assess lumbar loads during patient handling (Doss et al., 2018). The PostureCoach can assess lumbar spine flexion related to lumbar loads by two inertial measurement units (Doss et al., 2020). A previous study suggested that the PostureCoach could be applied for preventing lower back pain among caregivers (Doss et al., 2020). These studies provide reducing lumbar load, but these strategies and device are not enough for preventing lower back pain because these does not consider quantitative required force and lumbar loads. The required force is important for preventing lower back pain since it is considered that lumbar loads eventually depend on required force because of the weight and remained the ability of the patient. Therefore, this study focused on the relationship between required force and lumbar loads for further prevention of lower back pain.

Figure 1 shows the required force while supporting standing-up, which is a kind of patient handling. In supporting standing-up, the required force is considered to be the difference between the patient's weight and ground reaction force exerted by the patient. Nakano et al. (2019) suggested that wearable force shoes could measure the required forces while supporting standing-up (Nakano et al., 2019). Regarding lumbar loads, stress of the vertebral (L4–L5) joint and activities of spinae erector muscle are considered as important factors. (Kitagawa et al., 2019; Ning, 2017; Schibye et al., 2003). There are quantitative injury thresholds for preventing low back pain in these lumbar loads (Daynard et al., 2001; McGill et al., 1998; Waters et al., 1993). For example, 3400 N was recommended as the injury threshold for the compression stress of L4–L5 by the National Institute of Occupational Safety and Health (NIOSH) (Waters et al., 1993). In addition, previous studies considered that 500 N is injury threshold for shear stress of L4-L5 (Daynard et al., 2001; McGill et al., 1998). Furthermore, previous studies recommend that the activity of spinae erector muscle during lifting is less than 50-70 % of maximum voluntary contraction (Weames et al., 1994).

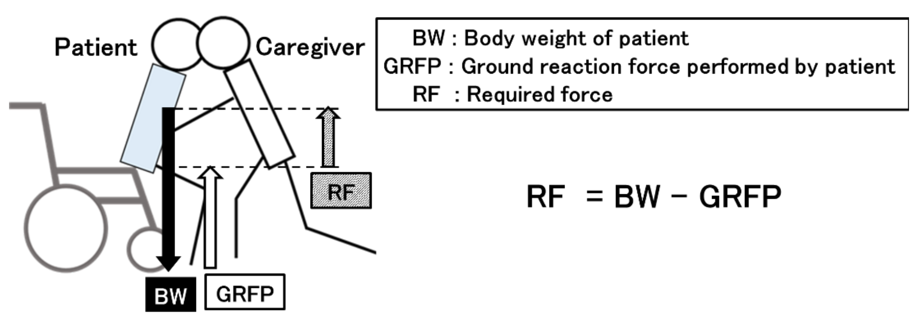

Figure 1. Required force for supporting standing-up

From these backgrounds, the quantitative relationships between the required force and lumbar loads are useful in preventing the low back pain of caregivers by wearable force shoes and injury threshold; however, these relationships were not quantitatively clarified. Therefore, this study investigated the quantitative relationships between the required force and lumbar loads during the support of standing-up motion, which caused the most lumbar load during patient handling (Schibye et al., 2003), using computational musculoskeletal simulation. Moreover, we present regression equations between the required force and lumbar loads such as vertebral stress and muscle activity based on computational musculoskeletal simulation. These regression equations will be useful to predict quantitative lumbar loads based on the required force for preventing low back pain by wearable force shoes and injury thresholds.

MATERIALS AND METHODS

The AnyBody Modeling System (AnyBody Technology A/S, Denmark) is a musculoskeletal simulator that was used to investigate the relationship between the required force and lumbar loads during supporting standing-up motion. The system has an anatomically detailed biomechanical model and numerous muscles (Damsgaard et al., 2006; De Zee et al., 2007). The muscle strength and stress of the vertebral are calculated based on moment equilibrium equations using an optimization algorithm and inverse dynamics technique in the AnyBody Modeling System (Damsgaard et al., 2006). A study reported that the AnyBody Modeling System could predict the stress of L4–L5 joint during the lifting motion in closer agreement with *in vivo* data than other equation models and musculoskeletal simulators (Rajaee et al., 2015), suggesting that it is suitable to investigate the lumbar loads in supporting standing-up, which is similar to the lifting motion.

In this study, the simulated musculoskeletal model supported the standing-up motion based on a designated pelvic position in a computer environment. This musculoskeletal model was validated in our previous study (Kitagawa et al., 2019) and we found that it could evaluate the compression stress of L4–L5 joint while supporting standing-up by comparing with previous studies (Chaffin, 2005; Kitagawa et al., 2019; McGill & Norman, 1985). This model included characteristics of the muscles such as isometric force, fiber length, shortening velocity due to body based on body weight and height. Table 1 reveals the parameters of the simulated musculoskeletal model and supporting standing-up motion. Table 2 shows number of muscles in each body part of the musculoskeletal model. These parameters were determined based on the validations in our previous study (Kitagawa et al., 2019) and standard musculoskeletal model in the AnyBody Modeling System. Figure 2 reveals the supporting standing-up motion performed by the musculoskeletal model. The left foot was defined as the front foot and the right foot was defined as the rear foot. The arrows that are placed on the hands vertically in Figure 2 are the variable required force for this supporting standing-up motion. In this study, we investigated lumbar loads with different required forces (range: 0–630 N, interval: 90 N) by AnyBody Modeling System. The maximum, minimum and average values for compression stress, anterior/posterior shear stress and medial/lateral shear stress of the L4–L5 joint were calculated from time series data of each motion performed with different required force. In addition, average values for activity of spinae erector muscle of each side (left/right) were also evaluated.

These muscle activities were normalized by muscle physiological cross-sectional area based on body parameters such as height and weight defined by the AnyBody Modeling System. When this normalized index is more than 1.0, it is considered that muscle activity exceeds limits of the musculoskeletal model. These lumbar loads were calculated by inverse dynamics-based optimization.

Table 1
Parameters of the musculoskeletal simulation

Musculoskeletal Model	Body Height	1.8 m
	Body Weight	75 kg
Simulated Motion	Patient Handling	Supporting Standing
	Required Force	0-630 N
	Motion Time	0.8 seconds
	Sampling	100 Hz

Table 2
Number of muscles in each body part of the musculoskeletal model

Body Part	Number of Muscle
Neck	61
Upper Limb	284
Trunk	203
Lower Limb	330
Total	878

Correlation coefficients and regression equations were calculated as quantitative relationships between lumbar loads and the required force. Pearson's correlation coefficients between lumbar loads and the required forces were calculated using the EZR software (Kanda, 2013), which was developed by R programming language. The significant level was $p < 0.05$. The linear regression equations and determination coefficient between lumbar loads and the required forces were calculated by Microsoft Excel 2016 (Microsoft, USA).

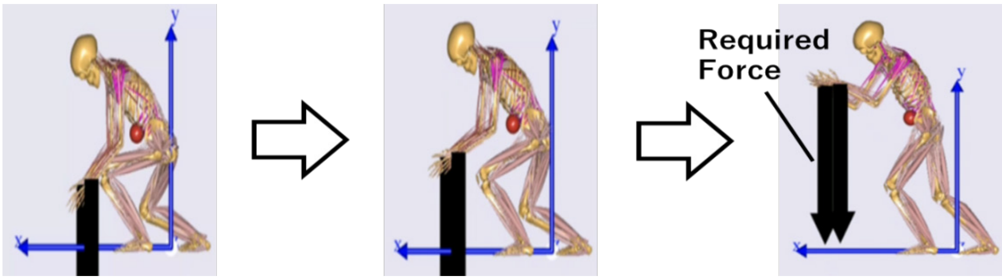

Figure 2. Supporting standing-up motion in computational simulation

RESULTS AND DISCUSSIONS

Table 3 shows correlation coefficients between the required force and each lumbar load. There were high significant correlations between the required force and all lumbar loads ($r > 0.9$, $p < 0.01$). Figure 3 – Figure 6 show scatter plots for the required force and each lumbar load. All lumbar loads had positive linear relationship with the required force. These high significant correlations and scatter plots suggest positive linear relationships between the required force and lumbar loads in the supporting standing-up motion. These trends are consistent with the result of a previous study related to common lifting task (Merryweather et al., 2009). Table 4 shows regression equations and determination coefficients for each lumbar load. Regression equations with high determination coefficients ($R^2 > 0.9$) were obtained for all lumbar loads. These high determination coefficients suggest that these regression equations obtained from computational musculoskeletal simulation could be used for prediction of lumbar loads of L4-L5 joint and erector spinae muscle.

Table 3

Correlation coefficients between the required force and lumbar load

Parameters Related to Lumbar Load	Correlation Coefficient (with Required Force)	p-value
Average of Compression Force of L4-L5	0.998	p < 0.01
Maximum Value of Compression Force of L4-L5	0.999	p < 0.01
Minimum Value of Compression Force of L4-L5	0.996	p < 0.01
Average of Anterior / Posterior Shear Force of L4-L5	0.999	p < 0.01
Maximum of Anterior / Posterior Shear Force of L4-L5	0.999	p < 0.01

Table 3 *(Continued)*

Parameters Related to Lumbar Load	Correlation Coefficient (with Required Force)	p-value
Minimum of Anterior / Posterior Shear Force of L4-L5	0.998	$p < 0.01$
Average of Medial / Lateral Shear Force of L4-L5	0.998	$p < 0.01$
Maximum of Medial / Lateral Shear Force of L4-L5	1.000	$p < 0.01$
Minimum of Medial / Lateral Shear Force of L4-L5	0.995	$p < 0.01$
Average of Muscle Activity in Left Sinae Erector Muscle	0.998	$p < 0.01$
Average of Muscle Activity in Right Sinae Erector Muscle	0.994	$p < 0.01$

Table 4

Regression equations and determination coefficients for lumbar load

Parameters Related to Lumbar Load	Regression Equations x : Required Force [N] y : Lumbar Load [N]/[-]	Determination Coefficient
Average of Compression Force of L4-L5 [N]	$y = 12.2x + 1581.4$	0.995
Maximum Value of Compression Force of L4-L5 [N]	$y = 13.8x + 1760.6$	0.997
Minimum Value of Compression Force of L4-L5 [N]	$y = 10.936x + 1455.8$	0.992
Average of Anterior / Posterior Shear Force of L4-L5 [N]	$y = 2.2437x + 389.11$	0.998
Maximum of Anterior / Posterior Shear Force of L4-L5 [N]	$y = 2.854x + 329.3$	0.999
Minimum of Anterior / Posterior Shear Force of L4-L5 [N]	$y = 1.7248x + 263.56$	0.996
Average of Medial / Lateral Shear Force of L4-L5 [N]	$y = 0.913x + 115.64$	0.997
Maximum of Medial / Lateral Shear Force of L4-L5 [N]	$y = 1.0837x + 149.97$	0.999

Table 4 *(Continued)*

Parameters Related to Lumbar Load	Regression Equations x : Required Force [N] y : Lumbar Load [N]/[-]	Determination Coefficient
Minimum of Medial / Lateral Shear Force of L4-L5 [N]	y = 0.6221 x + 52.694	0.990
Average of Muscle Activity in Left Sinae Eector Muscle [-]	y = 0.0027 x + 0.3016	0.995
Average of Muscle Activity in Right Sinae Eector Muscle [-]	y = 0.0008 x + 0.1375	0.989

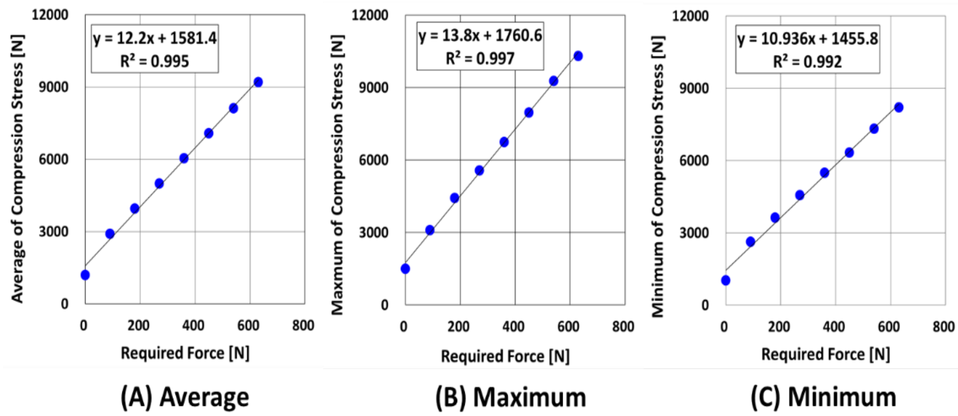

Figure 3. The scatter plot between the required force and compression stress of L4–L5

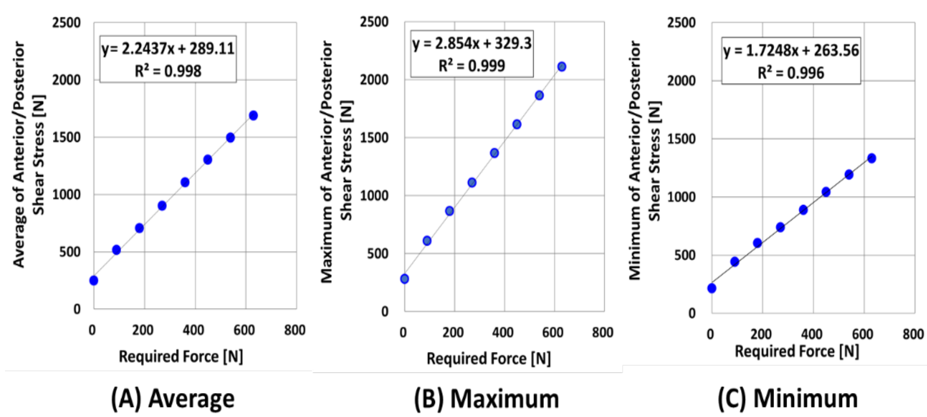

Figure 4. The scatter plot between the required force and anterior/posterior shear stress of L4–L5

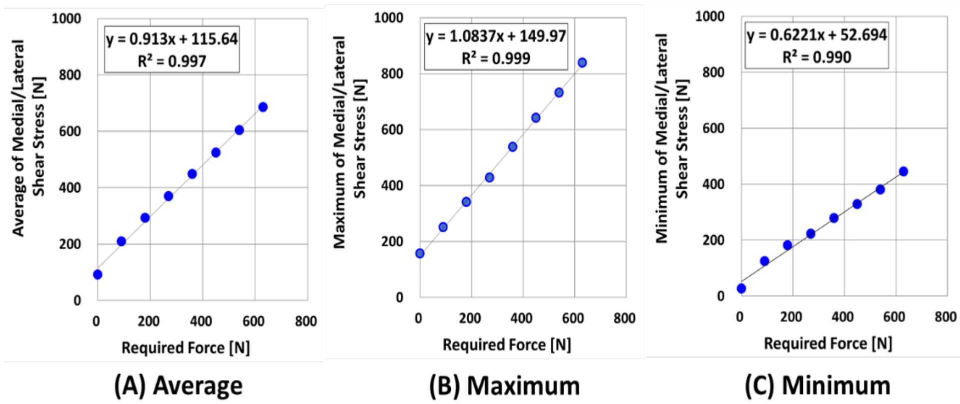

Figure 5. The scatter plot between the required force and medial/lateral shear stress of L4–L5

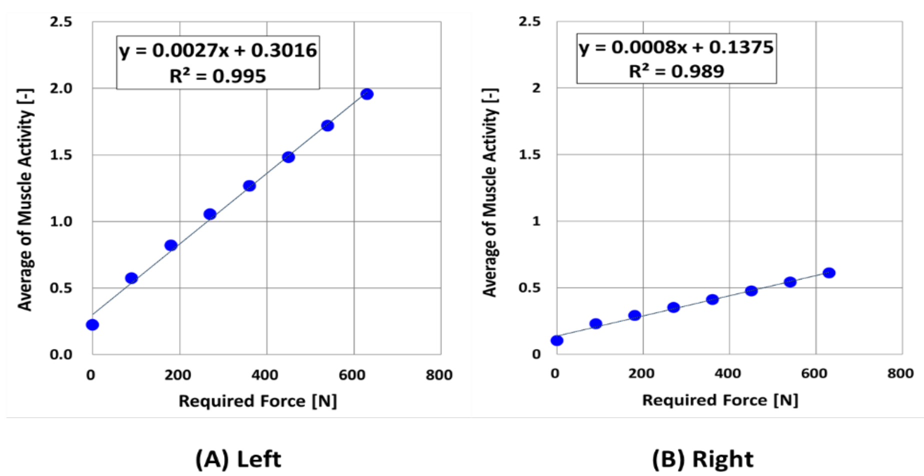

Figure 6. The scatter plot between the required force and activity of spinae erector muscle (average value)

In this paper, we consider about the relationship between compression stress of the L4-L5 joint and the required force as an example of using regression equations. The regression equation for the maximum value of compression stress of L4–L5 joint suggests the possibility that when the required force is more than 120 N, the compression stress exceeds 3400 N, which was defined as injury threshold by NIOSH (Waters et al., 1993). Based on these results, caregivers should be careful with the required force while supporting standing-up based on the weight and remained ability of each patient for preventing low back pain. Furthermore, these results suggest that when the required force is more than 120 N during supporting standing-up motion, a caregiver should reduce the lumbar loads by posture modification, working with multiple caregivers, or using assistive devices.

However, it is considered that using multiple caregivers or assistive devices are limited for time, efficiency, cost, and workspace. Therefore, a caregiver should practice a suitable posture and movement for preventing low back pain during patient handling such as supporting standing-up. For example, pulling instead of lifting procedures (Schibye et al., 2003) and the body mechanics theory (Ibrahim & Elsaay, 2015; Itami et al., 2010; Karahan & Bayraktar, 2004) may be applied to reduce lumbar load. Moreover, our previous study found that the opening stance length and width of caregiver was possibly useful for reducing the L4–L5 joint stress (Kitagawa et al., 2019). The findings of this study may be used for quantitative prevention of low back pain among caregivers based on the relationship between the required force and compression stress of the L4–L5 joint with injury threshold of NIOSH. Then, we also consider the relationship between activities of erector spinae muscle and the required force. *Figure 6* showed that when required force was more than 260 N, activity of left erector spinae muscle exceeded 1.0 as limit of the musculoskeletal model. Therefore, it is considered that the required force more than 260 N causes of fatigue or pain for erector spinae muscle in supporting standing-up. Thus, our regression equations obtained from the musculoskeletal simulation contributes to quantitatively consider lumbar loads of caregiver during patient handling based on injury thresholds and the required force.

A potential limitation is that there are differences between this simulation and the actual patient handling motions because of some factors such as the patient weights and trajectory of center of gravity are limited. This study is unable to investigate and correlate the patient and the caregiver, because we could not build a patient model. Thus, further study using new simulation environment includes patient model is necessary. This study could not simulate other patient handlings besides supporting standing-up. Future studies must investigate the other patient handlings that lead to low back pain, such as patient transfer and repositioning on the bed (Schibye et al., 2003). Our musculoskeletal simulation could not change several parameters, such as body height, body weight, and motion time because we validated this model for one setup of body parameters (body height 1.8 m, body weight 75 kg) (Kitagawa et al., 2019). In this paper, lumbar loads were not underestimated because we focused on a tall or chubby person who caused larger lumbar loads. However, future study should build model that could change parameters via further validations. The relationships between required force and lumbar loads obtained from this study are limited to only linear relationships. There is possibility that actual relationships are not only linear. Therefore, we will consider new simulation model that includes actual characteristics of muscle obtained from electromyography (EMG) in future works. Accordingly, we will build and verify new musculoskeletal model that is improved these limitations. Subsequently, we will investigate the relationship between the required force and lumbar loads in various parameters and several types of patient handling.

CONCLUSION

In this study, we investigated the quantitatively relationships between the required force and lumbar load such as vertebral stress and muscle activity in supporting standing-up by computational musculoskeletal simulation. The results showed that there were high significant correlations between the required force and all lumbar loads ($r > 0.9$, $p < 0.01$). In addition, regression equations with high determination coefficients ($R^2 > 0.9$) were obtained for each lumbar load. These regression equations contribute to quantitatively consider lumbar loads of caregiver during patient handling based on injury thresholds and the required force.

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