

Original Paper

Fluctuation Mechanism of Horizontal Force Applied to Buttocks Varies Depending on Difference in Rotational Axis Position of Back Support in a Reclining Wheelchair

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Abstract

The purpose was to investigate the cause of the increased horizontal force applied to the buttocks in the fully reclined position of back support on a reclining wheelchair with a rotational axis of back support which was located at the same position as the greater trochanter. The subjects were 15 healthy adult men. The forces were measured using a force plate on the experimental chair. And, we measured the trunk sliding distance along the back support. A comfortable sitting posture in the chair was selected for measurement. Under the rear-axis condition, the rotational axis of the back support was located at the point farthest back in the seat. Under the trochanter-axis condition, the rotational axis was located at the same position as the greater trochanter. In the fully reclined position, the horizontal forces under the rear-axis and trochanter-axis condition were 9.4 ± 1.2 and $15.6 \pm 1.7\%$ Body Weight, respectively ($p < 0.01$), and the trunk sliding distances were 71.3 ± 10.6 and -1.3 ± 7.4 mm, respectively ($p < 0.01$). These results suggested that the horizontal forces applied to the buttocks were changed by the trunk sliding along the back support in the fully reclined position.

1. Introduction

The Center for Medicare Services [1] reported that in fiscal year 2007, average cost per ulcer for Medicare patients with decubitus ulcers was \$43,180. In addition, in 2006, Reddy et al. estimated \$11 billion was spent on the treatment of decubitus ulcers in the USA [2]. Moreover, because decubitus ulcers do not heal easily, preventing them is of the utmost importance. Therefore, decubitus ulcers represent a serious health problem.

The etiology of decubitus ulcers is multifactorial and does not depend solely on pressure. There are

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four known mechanisms that contribute to decubitus ulcer formation: ischemia, lymphatic compromise, reperfusion injury, and sustained deformation under high loads. Factors such as fecal and urinary incontinence, tissue maceration, and malnutrition also play important roles in the development of decubitus ulcers because they modify the effect of external loads on tissue [3]. Furthermore, Husain [4] reported that the tolerance of tissue to external load depends on the duration of the exerted load. The external load, which includes pressure, friction, and shear force, is an important factor in decubitus ulcer formation. Although seemingly innocuous, friction and shear force, can increase the risk of clinical injury for both patients and practitioners [5]. Therefore, reducing shear force is important in the prevention of decubitus ulcers.

Wheelchairs with reclining a back support are often used for individuals with leg and trunk disorders including post-apoplectic hemiplegia and spinal cord injury. People who have difficulty sitting in the hospital can be more easily transported in wheelchairs with reclining back support. However, there are concerns regarding the use of reclining wheelchairs. First, individuals with flaccid hemiplegia often slide forward in such wheelchairs when returning to a seated position from a reclined position. Many wheelchair users who need reclining back support cannot correct this slouching posture unassisted; this leads to a sacral sitting posture and results in increased shear force on the sacrum, predisposing the individual to a sacral decubitus ulcer [6]. To overcome these problems, reclining wheelchairs with tilting seats have recently begun to be used in hospitals and nursing homes. Jan et al. [7, 8] suggested that wheelchairs that can tilt and recline can enhance skin perfusion over the ischial tuberosities without reducing sacral skin perfusion when moving the person from an upright to a tilted and reclined position. However, wheelchairs with tilting seats remain uncommon. Therefore, it is important to evaluate the reduction in the shear force applied to buttocks while such a wheelchair's back support is reclined.

We previously investigated the mechanism of fluctuation in shear force applied to the buttocks during the reclining of a wheelchair's back support [9]; shear force applied to the buttocks is greatest as the positions of the rotational axis of the back support and trunk-pelvis are separated. This suggests shear force could be reduced by shortening the distance between the rotational axis and hip joint. We also investigated the influence of the rotational axis position of the back support on shear force by measuring the shear force under different rotational axis positions while the back support was reclined [10, 11]. When a participant and the back support are returned to an upright position, the shear force in the trochanter-axis condition, in which the position is near the hip joint, is approximately 40% less than that in the rear-axis condition, in which the subject is farthest back in the seat. However, in the fully reclined position, the shear force in the trochanter-axis condition was approximately 35% higher than that in the rear-axis condition. In these previous studies, despite these findings as well as measurements of forces applied to buttocks and back support, the cause of the increased shear force in the fully reclined position remains unknown.

Besides our previous study, no studies have investigated the influence of the rotational axis position of a wheelchair's back support on the shear force applied to the buttocks during back support reclining. In addition, the NPUAP guidelines recommend that considerations be given to seated posture in order to prevent decubitus ulcer formation [12]. Also, seated posture is a major factor in the etiology of decubitus ulcers and significantly affects the comfort, function, physiology, mobility, and cosmetic features of the spine [13]. Therefore, the purpose of this study was to investigate the cause of the increased shear force in the fully reclined position measuring the forces applied to buttocks and the trunk sliding distance along the back support with the aim of contributing to the prevention of decubitus ulcers in people sitting in wheelchairs with a reclining back support.

2. Methods

2.1. Study design

This study design was an experimental study. This study was conducted with the approval of the Research Ethics Committee of Kawasaki University of Medical Welfare (approved no. 415) and conformed to

the tenets of the Declaration of Helsinki.

2.2. Participants

The participants included 15 healthy adult men without leg and/or trunk disease (mean age, 22.8 ± 3.6 years; height, 172.5 ± 4.8 cm; body weight, 67.7 ± 9.5 kg). Participants were excluded if they experienced pain while sitting on a chair or had back pain, a history of surgery, rheumatism, or neurologic disorders.

2.3. Materials

We used an experimental chair with electric controls for reclining the back support (Hashimoto Artificial Limb Manufacturer, Okayama, Japan). The dimensions of the experimental chair are as follows: back support height, 97 or 104 cm (it varies according to the experimental conditions); seat depth, 40 cm; backward angle of seat, 0° ; reclining angle of back support, $10\text{-}40^\circ$; angular velocity at which the back support reclined, $3^\circ/\text{s}$. The chair's back support was covered with artificial leather. By inserting L-shaped pieces at the junction between the back support and seat frame, the position of the rotational axis of the back support could be adjusted without altering the relative positions of the back support or seat frame. In inserting L-shaped pieces, as the back support reclined, the bottom edge of the back support shifted to downward from the rotational axis of the back support and the distance between the seat and top of the back support decreased 5 cm (Fig. 1).

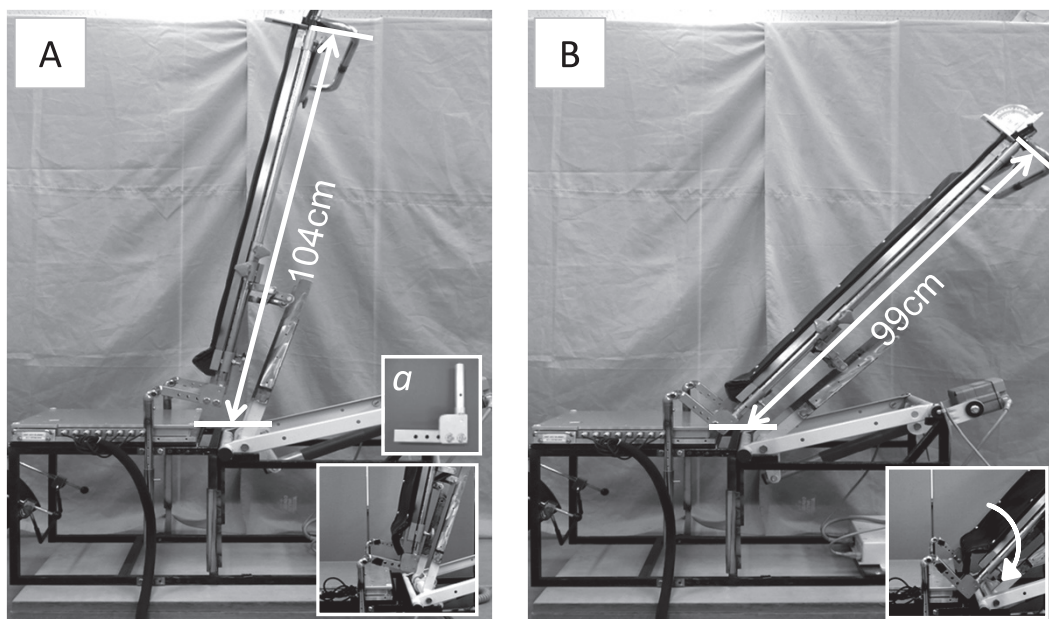


Fig. 1 Experimental chair (In inserting L-shaped pieces)

A: the initial upright and returning to the upright position B: the fully reclined position

As the back support reclined, the bottom edge of the back support shifted to downward from the rotational axis of the back support and the distance between the seat and top of the back support decreased 5 cm.

a: L-shaped pieces

For measurements, each participant sat comfortably with bilateral symmetry and rested on the back support and force plate. The participants' posture was checked such that the thoracic and lumbar spine in the frontal plane did not lean laterally by visually and manually inspecting the sternum and abdominal line. In addition, to achieve constant friction between each participant's clothing and seat surface, all participants wore 100% cotton clothing for this experiment. As the smooth metal surface of the force plate was

conducive to the participant sliding forward in the chair, a rubber net was laid over the plate to minimize sliding and the risk of postural collapse. The coefficients of friction were calculated on the basis of the maximum static friction force measured using a pull-tension gauge and weight; the coefficients of friction between clothing and the rubber net, the rubber net and surface of the force plate, and the surface of the back support and clothing were 0.9, 0.8, 0.4, respectively. To reduce the effects of differences in the positions of the lower extremities, the horizontal thigh angle was adjusted by elevating the feet with wooden boards stacked under the experimental chair [14], and the foot position was adjusted so that the lower legs were perpendicular to the feet [15]. Furthermore, to reduce the resistance of the lower extremities, a roller board was placed under the participants' feet. Participants were instructed to fold their arms in front of their chest in a relaxed state and to not intentionally change their body position during the experiment. Kemmoku et al. [16] reported that the vertical and horizontal forces applied to the sacrococcygeal and ischial tuberosity areas increase in a seated posture as the angle of pelvic tilting increases. Thus, each participant's buttocks were positioned so that the back support and dorsal surface were in contact to ensure consistency in the pelvic tilting angle among the experimental conditions.

Two experimental conditions were tested. Under the rear-axis condition, the rotational axis of the back support was located at the same height as the seat and the joint between the seat and back support, which was defined as the point farthest back in the seat. Under the trochanter-axis condition, the rotational axis was located at 13 cm in front of the point farthest back in the seat and 7.5 cm above the seat, so that the buttocks-trochanterion distance in a seated position was 12.8 ± 1.1 cm and the height of the trochanterion above the seat was 7.1 ± 7.0 cm in a young Japanese adult male [17] (Fig. 2).

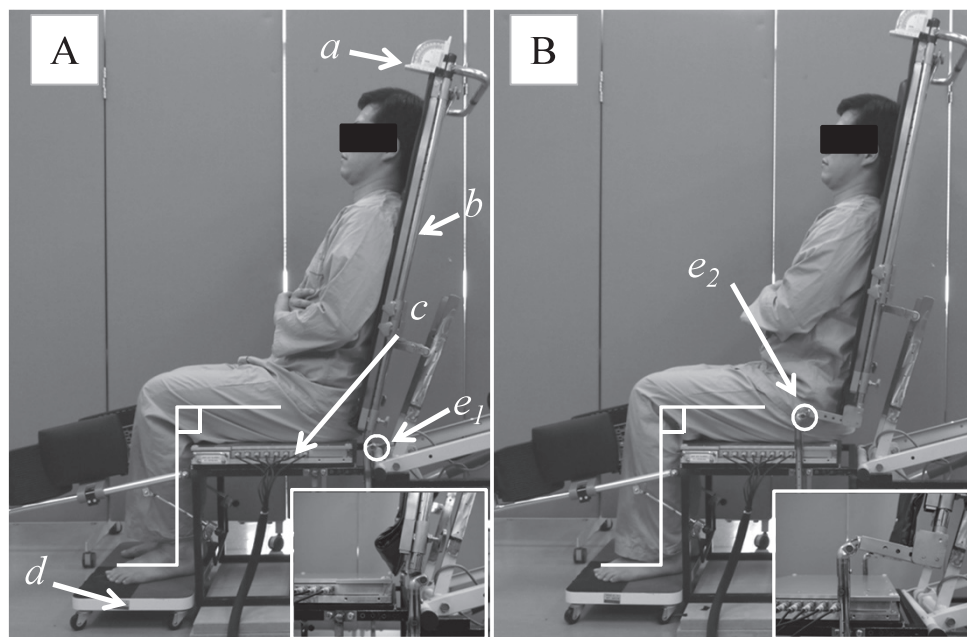


Fig. 2 Measured posture & experimental conditions

A: the rear-axis condition B: the trochanter-axis condition

a: level goniometer b: experimental chair (height of back support: 97 or 104 cm, depth of seat: 40 cm, backward angle of seat: 0° , reclining angle of back support: 10° - 40° , and angular velocity at which back support reclines: $3^\circ/\text{s}$) c: force plate d: roller board
 e_1 : The rotational axis of back support was located at the same height as the seat and the joint between the seat and the back support. e_2 : The rotational axis was located at 13 cm forward of the point farthest back in the seat and at a point 7.5 cm above the seat.

2.4. Measurement of the forces applied to the buttocks and the trunk sliding distance along the back support

To investigate the cause of the increased shear force to the buttocks, we measured the horizontal and normal forces, and recorded videos when the back support was reclining. The NPUAP [18] defined “shear” as “an action or stress resulting from applied forces which causes or tends to cause two contiguous internal parts of body to deform in the transverse plane”. As measuring shear force is difficult, we measured the horizontal and normal forces to represent the shear force. The horizontal and normal forces applied to the buttocks were measured using a force plate (400 x 400mm; sampling frequency, 100Hz; Kyowa Electronic Instruments, Tokyo, Japan); it measured the reaction force in the posterior direction, which is equivalent to the horizontal force in the anterior direction. Furthermore, we measured the trunk sliding distance along the back support (BS) by recorded moving picture. Videos of the trunk and back support were taken from the left side using a digital video camera (Panasonic, Osaka, Japan) for the duration of back support movement. Dartfish TeamPro Data 6.0 video analysis software (Dartfish, Fribourg, Switzerland) was used to measure the trunk sliding distance along the back support. The distance was defined as:

$$BS = Va - Vi$$

where Va and Vi correspond to the distances between the acromion and reference point B projected on the back support plane, respectively, after a position of back support during reclining (a) and an initial upright position (i) [19] (Fig. 3).

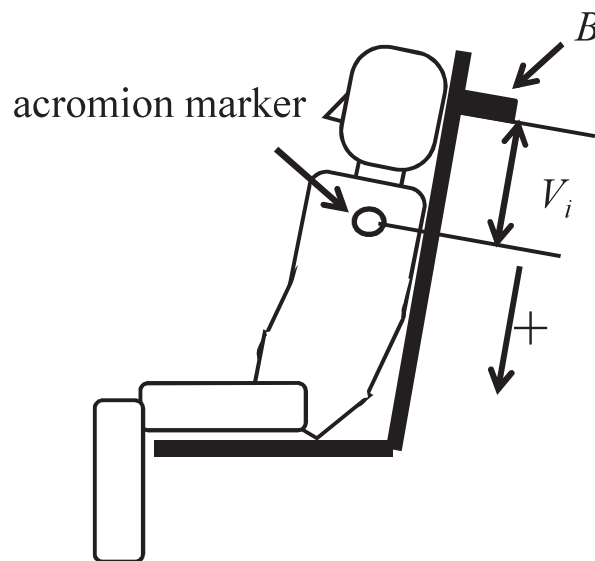


Fig. 3 The definition of sliding along the back support [19]

V_i : distance between reference point B and the acromion marker along the back support plane.

B: the basis of point on the back support.

+: the trunk was slid farther downward.

2.5. Experimental protocol

To correct for the influence of each participant's postural collapse during measurement, measurements were performed 10 seconds after the posture was set. Regarding the angle of back support inclination, Park et al. [20] reported that decubitus ulcers may be prevented or diminished in tetraplegia patients when the back support angle of the wheelchair is more than 120°, which is similar to 30° from vertical. Accordingly, the experimental back support was reclined at increasing angles, beginning at the fully upright position of 10° from the vertical (initial upright position, IUP), proceeding to a fully reclined position (FRP) of 40° from the vertical, and finally returning to the upright position (RUP). The times required to measure the forces in the IUP, FRP, and RUP were 5, 10, and 5 seconds, respectively. For each condition, we used the

average of the horizontal and normal forces applied to the buttocks after measuring 201 stable samples for each participant. The two conditions were measured in random order with three trials for each condition. If the participant could not continue sitting owing to intolerance or danger of sliding out of the chair, the experiment was stopped for safety reasons. Between each trial, the participants were asked to stand up and relax for a 1-minute break.

2.6. Statistical analysis

In order to correct for the effects of body weight, the measured horizontal and normal forces applied to the buttocks were normalized by body weight (percent body weight; %BW), on the basis of the raw data from the force plate. Preliminary analysis of the forces applied to the buttocks and sliding along the back support was performed using Shapiro-Wilk normality test. To investigate the influence of the back support rotational axis position, the forces applied to the buttocks and sliding distance in the three reclining positions were compared between the two experimental conditions. Data were analyzed by paired t-tests. To investigate the changes in the forces caused by reclining the back support, the forces created in the two experimental conditions were compared among the three reclining positions. The statistical analysis involved one-way analysis of variance (ANOVA) and Bonferroni's multiple comparison tests as a post hoc test. All statistical analyses were performed using the Statistical Package for the Social Sciences (SPSS) version 16.0J for Windows (SPSS, Chicago, IL, USA). The level of significance was set at $p < 0.05$.

3. Results

Tables 1 and 2 show the horizontal and normal forces applied to the buttocks and Table 3 shows the sliding distance along the back support.

Table 1 Horizontal force applied to buttocks on various back angles

	IUP ^{ns.}	FRP ^{**}	RUP ^{**}
the rear-axis condition ^a	10.6 ± 1.9	9.4 ± 1.2	18.7 ± 3.7
the trochanter-axis condition ^b	10.2 ± 1.2	15.6 ± 1.7	11.0 ± 1.7

IUP: initial upright position; FRP: fully reclined position; RUP: returning to an upright position.

All measurements are in the form mean ± standard deviation (percentage body weight).

** : compared between the two experimental conditions, $p < 0.01$.

^a: compared the RUP with the other positions, $p < 0.01$.

^b: compared the FRP with the other positions, $p < 0.01$.

Table 2 Normal force applied to buttocks on various back angles

	IUP ^{ns.}	FRP ^{**}	RUP ^{**}
the rear-axis condition ^c	72.2 ± 2.0	58.7 ± 4.1	82.9 ± 4.0
the trochanter-axis condition ^d	72.1 ± 2.2	62.5 ± 5.4	72.2 ± 2.8

IUP: initial upright position; FRP: fully reclined position; RUP: returning to an upright position.

All measurements are in the form mean ± standard deviation (percentage body weight).

** : compared between the two experimental conditions, $p < 0.01$.

^c: compared among the three positions, $p < 0.01$.

^d: compared the FRP with the other positions, $p < 0.01$.

Table 3 Sliding distance along the back support on various back angles

	FRP ^{**}	RUP ^{**}
the rear-axis condition	71.3 ± 10.6	14.9 ± 9.2
the trochanter-axis condition	-1.3 ± 7.4	2.1 ± 5.1

IUP: initial upright position; FRP: fully reclined position; RUP: returning to an upright position.

All measurements are in the form mean ± standard deviation (mm).

** : compared between the two experimental conditions, $p < 0.01$.

A positive value indicates that the trunk is shifted to downward.

A negative value indicates that the trunk is shifted to upward.

Regarding the horizontal force, there were significant differences in the horizontal force between the two experimental conditions in the FRP and RUP ($p < 0.01$). In addition, under the rear-axis condition, the horizontal force differed significantly between the RUP and the other positions ($p < 0.01$). Under the trochanter-axis condition, the horizontal force differed significantly between the FRP and the other positions ($p < 0.01$).

Regarding the normal force, there were significant differences in the normal force between the two experimental conditions in the FRP and RUP ($p < 0.01$). In addition, under the rear-axis condition, the normal force differed significantly among the three positions ($p < 0.01$). Under the trochanter-axis conditions, the normal force showed differed significantly between the FRP and the other positions ($p < 0.01$).

Regarding the trunk sliding distance along the back support, there were significant differences in the sliding distance of the back support between the two conditions in the FRP and RUP ($p < 0.01$).

4. Discussion

This study examined the influence of the rotational axis position on the shear force applied to the buttocks in order to aid the prevention of decubitus ulcers in individuals using wheelchairs with reclining back supports. In the FRP under the trochanter-axis condition, the forward horizontal force applied to the buttocks increased significantly in comparison with that in the IUP as the back support reclined. Aissaoui et al. [19] reported that the trunk was slid downward relative to the back support as it reclines. However, under the trochanter-axis condition in the present study, the sliding distance along the back support indicated that the position of the trunk relative to the back support barely slid against the back support. Therefore, under the condition similar to the trochanter-axis condition, the positions of the rotational axis of the back support and trunk are similar. This and the sliding distance along the back support suggested the back support inclines while maintaining the parallel relations with the trunk. Furthermore, we previously [11] showed that the parallel force on the back support applied to the trunk scarcely fluctuates from the IUP to the RUP. Thus, these results suggested the parallel force on the back support is inhibited, increasing the maximum static friction force between the back support and trunk. The maximum static friction force is typically greater than the dynamic friction force. In particular, the finding that the trunk was able to resist the stronger parallel force better under the trochanter-axis condition than the rear-axis condition indicates the trunk slides downward relative to the back support. In addition, under the trochanter-axis condition, the end of the back support moved below the rotational axis of the back support and the distance between the seat and top of the back support decreased 5 cm as the back support reclined. These results, the difference in the friction force between the back support and trunk, as well as the change in the distance between the seat and top of the back support, collectively suggest the trunk slides downward against the back support as it reclines. Therefore, in the FRP, the forward horizontal force applied to the buttocks increased significantly under the trochanter-axis condition.

On the other hand, under the rear-axis condition, the forward horizontal force applied to the buttocks did not differ significantly between the FRP and IUP. Gilsdorf et al. [21] reported that the backward shear force applied to the buttocks increases as the back support reclines. The rotational axis the reclining back support of the wheelchair in that study was located at the same height as the seat, and the joint between the seat and back support was similar to the rear axis condition in the present study. In both studies, the parallel relations with the trunk were not maintained in either study because of the difference in the rotational axis position between the back support and trunk. In addition, Aissaoui et al. [19], who used a reclining wheelchair with a back support with a rotational axis position similar to the rear axis condition in the present study, found the pelvis was displaced backward as the back support reclined. In the study of Gilsdorf et al. [21], it might be guessed that the static friction force between the back support and trunk occurred more strongly, unless the trunk slid downward on the back support, than the static friction force of using the back support in this study by these results. We previously measured the fluctuation pattern of the parallel force on the back support applied to the trunk in the rear axis condition; as a result, the parallel

force increased to downward from the IUP to FRP [10]. Thus, under the rear-axis condition, the upward force caused a reaction force as a downward parallel force on the trunk. In addition, the trunk slid 70 mm down the back support as it reclined in this study. Therefore, the upward force applied to the trunk may be due to the dynamic friction force between the back support and trunk. Because the downward force applied to the trunk was decreased by the dynamic friction force, the forward horizontal force applied to the buttocks was approximately equal between the IUP and FRP.

Regarding the results in the RUP under the trochanter-axis condition, the forward horizontal force applied to the buttocks was significantly lower than that in the FRP and similar to that in the IUP as the back support returned to the upright position. Because of the back support, the distance between the seat and top of the back support decreased 5 cm in the FRP; as the back returned to the upright position in the RUP, this distance was greater than that in the FRP. Similar to the FRP, in the RUP, the sliding distance along the back support indicates that the trunk almost did not slide owing to the static friction force between the back support and trunk. Thus, the trunk might be carried backward as the back support reclines. As a result, in the RUP under the trochanter-axis condition, the horizontal force applied to the buttocks, which increased significantly in the FRP, decreased significantly to almost the same as that in the IUP.

Under the rear-axis condition, in the RUP, the forward horizontal force applied to the buttocks was significantly greater than that in the FRP. Aissaoui et al. [19] reported that returning the back support to the upright position causes an able-bodied subject's trunk to slide upward against the back support while the pelvis slides forward in the seat. Similarly, in the RUP in the present study, the trunk slid upward in contrast to that in the FRP. The trunk was pushed forward by the reaction force on the back support, thereby increasing the forward horizontal force on the buttocks [22]. When the back support is raised to the upright position, the force between the back support and trunk is released as a result of the trunk sliding upward against the back support. This consequently inhibits a remarkable increase in the horizontal force applied to the buttocks [9]. However, in the rear axis condition in which the rotational axis position varied, the normal force on the back support increased, because the inclination locus of the back support and trunk did not exhibit parallel relations [10]. Therefore, it is unlikely some force on the back support was released as a result of the trunk sliding against the back support; thus, the static friction force between the back support and trunk increased. Accordingly, the forward horizontal force on the buttocks increased remarkably in the rear axis condition.

Huang et al. [23] reported that the body of stroke patients with flaccid hemiplegia slide downward with respect to both the seat and back support by returning the back support to the upright position. These findings suggested that it is difficult for stroke patients with flaccid hemiplegia to reposition their body unassisted if it has slid downward in a reclining wheelchair in the IUP to FRP. The horizontal force loaded on the buttocks in a collapsed posture is obviously greater than that in the present study. In addition, we previously reported that repositioning the buttocks more forward increases the residual forward horizontal force after reclining the back support [24]. Therefore, reclining wheelchairs require a means to prevent the body from sliding downward. Carlson and Payette [25] described techniques for minimizing friction/shear forces in wheelchair seating through the orientation of the seat surface, positioning of foot supports, and use of low-friction seat cover materials. Furthermore, our previous results [9-11, 24] suggested reclining wheelchairs should have a way to adjust the rotational axis position of the back support such that it is close to the hip joint in order to decrease the horizontal force applied to the buttocks in the RUP. In addition to this function, the present results suggest the friction force between the back support and trunk should be regulated to enable the trunk to slide upward relative to the back support in the IUP to FRP and to slide downward in the FRP to RUP in order to decrease the horizontal force applied to the buttocks through the IUP to RUP.

Limitation

The main limitation of this study is that it included only healthy adult males. In addition, because the measurement times were short, the effect of delayed postural collapse was not evaluated. Furthermore, the form, material, and coefficient of friction of the experimental chair's seat differed from those used to measure the horizontal forces. Moreover, we did not consider factors that interact with the friction force, such as urinary incontinence and sweat, which affect many wheelchair users. Therefore, the present results should be extrapolated to actual wheelchair users with great caution.

5. Conclusion

We conjectured that the horizontal force applied to the buttocks affected the friction force between the trunk and the back support from these results. Reclining wheelchairs might have a function to regulate the friction force between the back support and trunk in order to prevent decubitus ulcer formation. However, we did not investigate this conjecture yet. Thus, we are planning to investigate the influences of the seat material and the friction force of the back support on the horizontal force applied to the buttocks while the wheelchair is reclining. These results will aid the development of reclining wheelchairs and ultimately reduce the occurrence of decubitus ulcers.

Declaration of interest

The authors report no conflicts of interest.

Acknowledgments

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