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Original Article

Effect of Rotational Axis Position of Wheelchair Back Support on Shear Force when Reclining

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Abstract. [Purpose] The purpose of this study was to investigate the influence of the rotational axis position of a reclining wheelchair's back support on fluctuations in the shear force applied to the buttocks while the back support is reclined. [Subjects] The subjects were 12 healthy adult men. [Methods] The shear force applied to the buttocks was measured using a force plate. This study used two different experimental conditions. The rotational axis of the back support was positioned at the joint between the seat and the back support for the rear-axis condition, and was moved 13 cm forward for the front-axis condition. [Results] With the back support fully reclined, the shear forces were 11.2 ± 0.8%BW and 14.1 ± 2.5%BW under the rear-axis and front-axis conditions, respectively. When returned to an upright position, the shear forces were 17.1 ± 3.1%BW and 13.8 ± 1.7%BW under the rear-axis and front-axis conditions, respectively. Significant differences appeared between the two experimental conditions ($p < 0.01$). [Conclusion] These results suggest that the shear force value could be changed by altering the position of the back support's rotational axis during reclining.

Key words: Decubitus ulcer, Shear force, Reclining wheelchair

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INTRODUCTION

Wheelchairs with reclining back supports are often used by individuals with leg and trunk disorders, such as those with post-apoplectic hemiplegia or spinal cord injuries. Back support plays a dominant role in maintaining the posture of wheelchair users. A reclining back support stabilizes the trunk of a wheelchair user's body and is also used to deal with postural hypotension in people with spinal cord injuries. However, in nursery homes for the elderly, the occurrence of decubitus ulcers has been reported in disabled individuals using wheelchairs with a reclining back support over long periods of time[1, 2)]. Many wheelchair users who need reclining back support cannot correct a collapsed posture on their own. Wheelchair users have often been observed to slide downwards in their chairs in facilities that provide health-care services for the elderly. We conjecture that greater shear force is loaded onto the buttocks of these individuals in the collapsed posture[3)], and that this may lead to the increased incidence of decubitus ulcers.

Guttmann[4)] attributed a larger role to shear force than pressure in reducing the vascular supply. In addition, Bennett et al.[5)] reported that a combination of pressure and shear force effectively promoted blood flow occlusion. Dinsdale[6)] studied the effects of various pressures on blood flow and ulceration with and without shear in normal and paraplegic swine. He found that in animals subjected to pressure and shear force, ulceration occurred at lower pressures than in those animals experiencing only pressure. To investigate the relationship between compressive pressure and shear force, Sakuta et al.[7)] measured the changes in blood flow due to such loads, suggesting that 50 mmHg of pressure and 9 kPa of shear force were nearly equivalent in biological soft tissue. Goossens et al.[8)] also reported that a shear force of 3.1 kPa significantly influenced the reduction in blood flow in the sacrum of healthy subjects, and indicated the importance of reducing the shear force for preventing decubitus ulcers in terms of blood flow.

Furthermore, there have been some reports of the aetiology of decubitus ulcers in recent years. Some investigators have hypothesized that ischemia alone cannot explain the aetiology of deep tissue injuries in decubitus ulcers, and that other mechanisms, particularly excessive cellular deformation, are likely to be involved[9–12)]. Linder-Ganz et al.[9)] reported that skeletal myocytes of rats can survive 2 hours of complete ischemia but die within 15 min of a load causing shear deformation of tissue. Stekelenburg and his associates[10)] conducted rat studies that isolated the effects of ischemia and shear loading, revealing that 2 hours of ischemic conditions caused by a tourniquet resulted in reversible tissue changes, whereas 2 hours of static loading with an indenter induced irreversible damage. The damaged areas corresponded to a region undergoing high shear strain as determined in separate experiments. Other

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studies involving static loading using animal modeling and finite-element modeling have suggested that shear deformation of tissue initiates short-term tissue damage. After the initiation of damage, ischemia may accelerate injury due to hypoxia, glucose depletion, and acidification[11, 12]. On the other hand, Lahmann and Kottner[13] reported that there is a strong relationship between friction forces and superficial skin lesions and between pressure forces and deep tissue injury. In addition, a systematic review by Reenalda and colleagues[14] discovered "a weak qualitative relation" between interface pressure and the development of decubitus ulcers. In fact, their study concluded that "no quantification of the predictive or prognostic value of interface pressure can be given." In any case, some investigators have concluded that there is a strong relationship between shear force and decubitus ulcers.

Therefore, we have focused on the fluctuation of the shear force applied to the buttocks while reclining the back support of a wheelchair. Gilsdorf et al.[15] studied the effect of the reclining angle of the back support on the shear and normal forces applied to the buttocks. They found that a shear force was applied to the buttocks in the posterior direction when the back support was reclined and in the anterior direction when it was returned to the upright position. Hobson[16] reported that a back support recline angle of 30° caused a 25% increase in the surface shear force as compared with a recline angle of 10° in subjects with spinal cord injuries. Bennett et al.[17] compared the shear and normal forces applied to the buttocks of normal and paraplegic subjects, and reported that the normal force did not differ significantly between the two groups. However, the shear forces applied for the sitting posture in paraplegic subjects were roughly three times those in normal subjects, and the rates of pulsatile skin blood flow volumes applied to the buttocks in sitting paraplegic subjects were only one-third of those of comparable normal subjects. Furthermore, in a previous study, we investigated the mechanism of the fluctuation in the shear force applied to the buttocks while a wheelchair's back support was reclined[18]. Our results suggested that the shear force applied to the buttocks changes more significantly as the axes of rotation for the back support and for the trunk–pelvis grow further apart. However, as far as we know, no existing studies have investigated the influence of the rotational axis position of a wheelchair's back support on the fluctuation in the shear force applied to the buttocks during reclining of the wheelchair's back support. The purpose of the experiment reported herein was therefore to investigate the influence of the difference in rotational axis position on the fluctuation in the shear force. We accomplished this by measuring the shear and normal forces applied to the buttocks and back support. It was hypothesized that the shear force applied to the buttocks would be reduced by moving the position of the rotational axis closer to the hip joint.

SUBJECTS AND METHODS

The subjects were 12 healthy adult men (age, 23.6 ± 6.3 years; height. 173.1 ± 3.1 cm; and body weight, 68.7 ± 8.5 kg). Those subjects who had pain while sitting on a chair, those who experienced back pain, those who had operations, and those who had rheumatism or any neurologic disorder were excluded from the experiment. This study was conducted with the approval of the Research Ethics Committee at the Kawasaki University of Medical Welfare (# 074), and informed consent was obtained from all subjects.

In the present study, the horizontal reaction forces were defined as the shear forces. The shear and normal forces applied to the buttocks were measured by using a force plate (K07-1712, Kyowa Electronic Instruments Co., Ltd., Tokyo, Japan). The force plate measured the reaction force in the posterior direction, which may be treated as equivalent to the shear force in the anterior direction. The sampling frequency was 100 Hz. In addition, a pressure and shear force sensor (Predia, Molten Corp., Hiroshima, Japan) was used in conjunction with a data logger (ZR-RX20V, Omron Corp., Kyoto, Japan) to measure the timing of the force applied to the back support. This sensor uses air displacement to measure pressure and a strain gauge to measure shear force. It is made of flexible plastic and has an elliptical shape. The Predia sensor can measure pressures ranging from 0 to 200 mmHg and shear forces ranging from 0 to 50 N[19]. The sensor is 28.14 cm^2 in size. In previous studies, such a sensor was adhered to a flat, rigid surface, and different wound dressings were evaluated by applying a horizontal displacement across the static sensor[20, 21]. The results of these previous studies suggested that the Predia sensor could perform measurements with high confidence under surface conditions similar to those used in the studies. However, because the measured surface conditions in the back support material and its form differed from those in the previous studies, only the fluctuation patterns of the forces applied to the back support were considered below.

The sensor was attached to the back at the location of highest pressure from the back support when the subject was sitting comfortably in the experimental chair. The location of the highest pressure was determined manually by the examiner. This occurred near the longissimus thoracis on the left side and near the 7th or 8th thoracic spinous process, and the locationwas similar for all subjects. The measured shear force was positive for a force directed downward from the trunk to the back support and negative for an upward force. We used an experimental chair with electrical controls for reclining the back support (Hashimoto Artificial Limb Manufacturer Co., Okayama, Japan). The dimensions of the experimental chair were as follows: height of back support, 97 cm; depth of seat, 40 cm; backward angle of seat, 0°; reclining angle of back support, 10–40°; and angular velocity at which the back support reclined, 3°/s. The chair's back support was covered with artificial leather. By inserting L-shaped pieces in the junction between the back support and the seat frame, the position of the rotational axis of the back support could be adjusted without changing the relative positions of the back support and the seat frame. The subject's posture for measurements was a comfortable sitting posture, resting on the back support and on the force plate in the experimental chair. In addition, to achieve constant friction between clothing and the surfaces of the seat, all subjects wore identical clothing made of 100% cotton. It is easy to slide on the smooth metal surface of the force plate. Thus, in order to prevent sliding and collapsing of posture on the force plate, a rubber net was laid over the plate. The coefficients of friction were 0.9 between the clothing and the rubber net, 0.8 between the rubber net and the surface of the force plate, and 0.4 between the surface of the back support and the clothing. These coefficients of friction were calculated based on the maximum static friction force measured using a pull tension gauge and a weight. 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[22], and the foot position was adjusted so that the lower legs were perpendicular to the feet[23]. Furthermore, to reduce the resistance of the lower extremities, a roller board was placed under the subjects' feet. In addition, participants were instructed to fold their arms in front of their chest in a relaxed state and not to intentionally change their body position during the experiment. Buttocks were positioned so that the distance from the back support to dorsal surface of the sacrum in the measurement posture was 3 cm[3].

Two experimental conditions were utilized. In the first, the rotational axis of the back support was positioned at the joint between the seat and the back support, which was defined as the point farthest back in the seat. We refer to this as the rear-axis condition. The second condition, which we refer to as the front-axis condition, had the rotational axis located 13 cm forward relative to the rear-axis condition, so that the buttocks–trochanterion length in a sitting posture was 12.8 ± 1.1 cm in a young Japanese adult male[24]. For the front-axis condition, the rotational axis was positioned slightly behind the hip joints of all subjects. To correct for the influence of the subject's collapse in posture when taking the measurements, measurements were performed 10 s after the posture was set. 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 returning to the upright position (returning to upright position: RUP). The time required to measure the shear force in each condition was 5 s in the IUP, 10 s in the FRP, and 5 s in the RUP. For each position, we used the average value of the shear and normal forces applied to the buttocks after measuring 201 stable samples for each subject (Fig. 1). The two conditions were measured in random order with one trial for each condition. We additionally considered the relationship between the forces applied to the buttocks and those applied to the back support by visually inspecting the data.

Statistical analyses: The measured shear and normal forces applied to the buttocks were normalized by body weight (percent body weight; %BW) based on the raw data from the force plate in order to correct for the effects of body weight. We used Shapiro-Wilk's normality test as a preliminary analysis of the shear and normal forces applied to the buttocks. In addition, to investigate the changes in the forces applied to the buttocks by reclining the back support, the forces in the two experimental conditions was compared among the three reclining phases. For statistical analysis, a paired t-test was performed with the level of significance set at $p < 0.05$. The statistical analysis involved one-way analysis of variance (ANOVA) and Bonferroni's multiple comparison tests with a level of significance of $p < 0.05$. The statistical analyses were performed using the Statistical Package for the Social Sciences (SPSS) ver. 16.0 J for Windows.

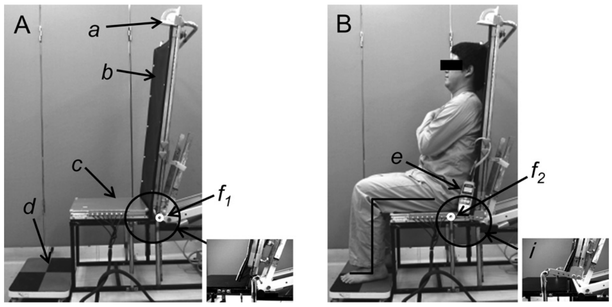

Fig. 1. Measurement posture (the IUP)
A. Rear-axis condition, B. front-axis condition, a. Level goniometer, b. experimental chair (height of back support, 97 cm; depth of seat, 40 cm; backward angle of seat, 0°; reclining angle of back support, 10°– 40°; and angular velocity at which back support reclines, 3°/s), c. force plate, d. Roller board, e. Predia sensor, f. rotational axis position of back support as the rear-axis condition (f_1) and the front-axis condition (f_2), i. L-shaped pieces

RESULTS

Table 1 shows the measured shear and normal forces applied to the buttocks, and Fig. 2 shows the wave representing the fluctuation pattern of the forces in a typical example.

For the shear force applied to the buttocks, a significant difference appeared between the two experimental conditions ($p < 0.01$). In the rear-axis condition, significant differences appeared between the RUP and the other positions ($p < 0.01$). In the front-axis condition, significant differences appeared between the IUP and the other positions ($p < 0.01$). The normal force shows no significant differences in the three reclining phases between the two conditions. For both experimental conditions, significant differences appeared among the three reclining phases ($p < 0.01$).

The fluctuation patterns for the forces were similar for all the subjects. The fluctuation phase of the shear force applied to the buttocks differed remarkably for each condition. This force showed remarkable fluctuation during the transition from the IUP to the FRP under the front-axis condition and during the transition from the FRP to the RUP under the rear-axis condition. The normal force decreased during the transition from the IUP to the FRP and increased during the return of the back support to the RUP under both experimental conditions. We next turn to forces applied to the back support. Under the rear-axis condition, the downward

Table 1. The forces on various back angles (n=12)

Shear force	$IUP^{n.s}$	FRP^{**}	RUP^{**}
The rear-axis [a]	10.0 ± 1.3	11.2 ± 0.8	17.1 ± 3.1
The front-axis [b]	10.6 ± 1.3	14.1 ± 2.5	13.8 ± 1.7
Normal force	$IUP^{n.s}$	$FRP^{n.s}$	$RUP^{n.s}$
The rear-axis [c]	75.9 ± 2.0	61.6 ± 4.9	82.5 ± 3.8
The front-axis [c]	75.5 ± 2.6	63.1 ± 4.9	82.3 ± 10.7

mean ± SD (%BW)
**: $p < 0.01$; comparing the front-axis with the rear-axis, a: $p < 0.01$; comparing the RUP with IUP and FRP, b: $p < 0.01$; comparing the IUP with FRP and RUP, c: $p < 0.01$; comparing among the three reclining phases, n.s.: not significant; comparing the front-axis with the rear-axis

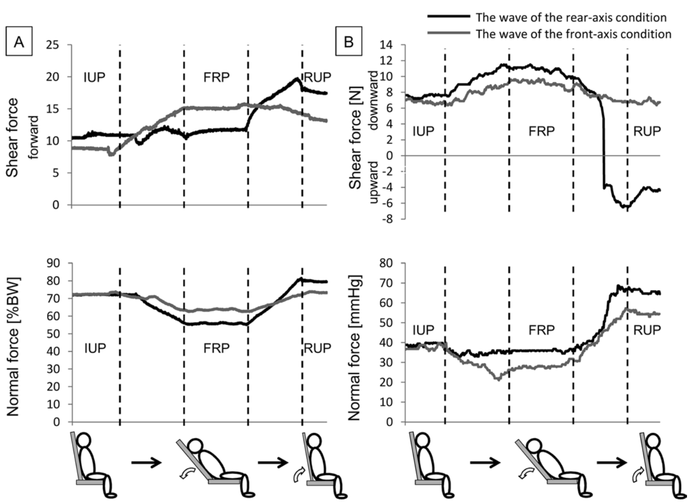

Fig. 2. The wave of the fluctuation pattern of the forces (the typical example)
A. Forces applied to buttocks, B. forces applied to back support

shear force decreased and the pressure increased linearly as the back support rotated from the FRP to the RUP, until the middle phase was reached with the back support at an angle of 15°. Then the shear force suddenly reversed to an upward direction, and the pressure suddenly increased during the transition to the RUP. Under the front-axis condition, none of the shear forces exhibited the remarkable change that happened for the rear-axis condition when rotating from the IUP to the RUP. In addition, the pressure decreased during the transition from the IUP to the FRP, and increased during the transition from the FRP to RUP.

DISCUSSION

The purpose of this study was to investigate the influence of changes in the back support rotational axis position on shear force fluctuation. Measurements of the shear and normal forces applied to the buttocks and back support were taken in order to contribute to the prevention of decubitus ulcers in individuals using wheelchairs with reclining back supports. It was hypothesized that moving the rotational axis closer to the hip joint would reduce the shear force applied to the buttocks. Carlson and Payette[25] described techniques to minimize friction/shear in wheelchair seating through orientation of the sitting support surface, positioning of foot supports, and the use of low-friction materials for seat covers. Furthermore, in a previous study, we investigated the influence of the distance between the position of the rotational axis of the back support and the hip joint on fluctuations in the shear force applied to the buttocks in a simulation of disabled individuals sliding downwards in wheelchairs. The results of these studies suggested that modifying wheelchair users' collapsed postures and releasing the remaining shear force as well as the back support itself are important in preventing decubitus ulcers when using reclining back supports in the RUP[26]. In this study, the influence of the position of the rotational axis of the wheelchair's back support on the fluctuation in the shear force applied to the buttocks while reclining the wheelchair's back support was investigated using a force plate and a Predia sensor, with the aim of contributing to the prevention of decubitus ulcer formation in people sitting in a wheelchair with a reclining back support. The results of this study show that the magnitude of the shear force applied to the buttocks in the front-axis condition was significantly higher than that in the rear-axis condition in the FRP. In addition, the magnitude of the shear force applied to the buttocks under the front-axis condition was significantly lower than that under the rear-axis condition in the RUP. The rotational axis position in the front-axis condition is closer to the hip joint, which is the rotational axis of the trunk and the pelvis in the horizontal plane. These results for the RUP may verify our previous suggestion that the shear force applied to the buttocks changes more greatly when the positions of the axes of rotation for the back support and for the trunk–pelvis are separated. However, these results stand in contradiction to the results for the FRP. As shown by the fluctuation pattern of the waveform in Fig. 2, the remarkable fluctuation phase of the shear force applied to the buttocks differed for each condition. This force showed remarkable fluctuation during the transition from the IUP to the FRP under the front-axis condition but showed this fluctuation during the transition from the FRP to the RUP under the rear-axis condition. The fluctuation pattern of the shear and normal forces applied to the back support showed significant variation toward the end of the transition from the FRP to the RUP under the rear-axis condition. Under the front-axis condition, the shear force applied to the back support did not show significant change such as occurred in the rear-axis condition, but the normal force decreased during the transition from the IUP to the FRP. Based on the friction force on the surfaces of the seat and the back support and the fluctuation pattern of the measurement forces, we discuss below the shear force applied to the buttocks in the FRP and the RUP.

In the FRP, significantly lower values of shear force on the buttocks were obtained under the rear-axis condition. In this study, an L-shaped part was used for adjusting the rotational axis position of the back support under the front-axis condition. Using this part, the back support can also move downward when it is tilted backwards. However, the buttocks cannot move downwards, so the seat supports the ischial tuberosity. The remaining downward force is channeled into the forward shear force applied to the buttocks. We therefore infer that the shear force applied to the buttocks increased under the front-axis condition.

In the RUP, the shear force applied to the buttocks under the front-axis condition was significantly lesser than that applied under the rear-axis condition. The posterior inclination angle of the back support and that of the trunk and pelvis changed under the front-axis condition, but the shear force applied to the buttocks and the back support showed no remarkable fluctuations during the transition from the FRP to the RUP. Furthermore, under the front-axis condition, the fluctuation pattern of the pressure applied to the back support did not show a sudden increase during the transition from the FRP to the RUP, which did occur under the rear-axis condition. If the trunk and pelvis remain parallel to the back support as it reclines, the primary force applied to the back support should be the normal force, since the head, trunk, pelvis, and arms are supported by the surface of the seat[18]. Under the front-axis condition, the results match this expectation, showing that the shear force applied to the back support did not vary during the reclining phase. This suggests that the trunk and pelvis remained parallel to the back support as it reclined because of the small distance between the rotational axis of the back support and the hip joint. Under the rear-axis condition, on the other hand, the fluctuation pattern of the shear force applied to the buttocks and the pressure applied to the back support showed a sudden increase.In addition, the shear force applied to the back support suddenly changed to an upward force when transitioning from the FRP to RUP. Because of the large distance between the rotational axis of the back support and the hip joint under the rear-axis condition, the inclination angle of the back support was different from the inclination angle of the trunk and pelvis. The vertical position of the pelvis cannot be changed to make the seat support the ischial tuberosity. Thus, the trunk slid downward relative to the back support as the back support reclined in the transition from the IUP to the FRP. Thereafter, in order to return the trunk to the upright position smoothly, the trunk must slide upward as the back support returns to the RUP. However, the inclination angle of the trunk–pelvis is increased under the rear-axis condition, so the influence of the sliding on the trunk is downward relative to the back support. The pressure applied to the back support also increases if the trunk and pelvis are tilted backward at a large angle. The reaction force applied to the back support has a strong relationship to the shear force applied to the buttocks[27, 28]. In addition, Gilsdorf et al.[15] reported that leaning forward, away from the back support, returned the shear force applied to the buttocks to a value close to that at the IUP after the back support reclined. That report suggested that the shear force applied to the buttocks could be reduced by raising the back from the back support and decreasing the reaction force. The front-axis condition effected these suggestions and effectively reduced the shear force applied to the buttocks when compared with the rear-axis condition. Therefore, adding an adjustment capability that brings the back support rotational axis as close to the hip joint as is the horizontal rotational axis of the trunk-pelvis may help reduce decubitus ulcers caused by reclining wheelchairs.

A limitation of this study was that the subjects were all healthy adult males. In addition, because the measurement times were relatively short, we could not evaluate the effect of postural collapse due to fatigue. Furthermore, the form, material, and coefficient of friction of the experimental wheelchair's seat were different from those when using the force plate to measure the shear force in the present study. Therefore, it would be difficult to directly extrapolate the results of this study to all cases of wheelchair use.

The results of the present study suggest that the shear force applied to the buttocks can be varied by changing the rotational axis position of the reclining back support. Making the position of the back support's rotational axis adjustable is necessary from the viewpoint of the prevention of decubitus ulcers. In the future, we plan to investigate the influence of the vertical position of the rotational axis of the back support, as well as the influence of back support materials. Furthermore, it is necessary to extend our research to include all wheelchair users.

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