Mechanism of fluctuation in shear force applied to buttocks during reclining of back support on wheelchair

Running title: Mechanism of fluctuation in shear force

Introduction

A systematic review by Reenalda *et al*. [1] "a weak qualitative relation" between interface pressure and the development of decubitus ulcers. In fact, the study concluded that "no quantification of the predictive or prognostic value of interface pressure can be given". On the other hand, Studies of decubitus ulcers have clarified that complex stress is generated inside the body. Not only compressive force but also shear force acts on the skin surface [2-5]. Dinsdale [2] studied the effect of reported pressure with and without shear in normal and paraplegic swine. He found that in those animals that received pressure and shear, ulceration occurred at lower pressure than in those animals that received only pressure. More than 20 years ago, Bennett *et al*. [3] reported that a combination of pressure and shear force effectively promoted blood flow occlusion. To investigate the relationship between compressive pressure and shear force, Sakuta *et al*. [4] measured the changes in blood flow due to these loads. Their results suggested that 50 mmHg of pressure and 0.9 N/cm^2 of shear force were nearly equivalent in biological soft tissue. Goossens *et al.* [5] also reported that a shear force of 3.1 kPa significantly influenced the reduction of blood flow in the sacrum of healthy subjects, and indicated the importance of reducing the shear force for the prevention of decubitus ulcers in terms of blood flow. These examples of research demonstrate the focus on the relationship between decubitus ulcer occurrence and shear force.

Wheelchairs with reclining back support are often used for individuals with leg and trunk disorders, such as those with post-apoplectic hemiplegia or spinal cord injuries. The back support plays a major role in supporting the posture of wheelchair users. People who experience difficulty with sitting in the hospital can be more easily carried in wheelchairs having reclining back support. Furthermore, reclining back support is used to treat postural hypotension in people with spinal cord injuries. These advantages of this functionality are well known. However, in recent years, decubitus ulcers have occurred when persons with disabilities must sit in a wheelchair with reclining back support for long periods of time in facilities providing health care services for the elderly [6, 7]. Many wheelchair users who need reclining back support cannot correct a collapsed posture by themselves. It is easy to guess that greater shear force is loaded to their buttocks in a collapsed posture.

Gilsdorf *et al.* [8] 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. Furthermore, in a previous study, we investigated the temporal elements of changes in the sitting pressure distribution that occurred while leaning against a back support to verify the onset mechanism of shear force in a comfortable sitting posture [9]. These results suggested that the sitting posture of people with disabilities collapsed owing to fluctuation in the reaction force from the back support associated with reclining the back support. The problem of disabled people shifting downward in their chairs was not reproduced during repeated reclines. Nevertheless, no studies exist on measurements of the shear forces on the buttocks and back support in a comfortable sitting posture when a wheelchair's back support was reclined. The purpose of this study was to investigate the mechanism of the fluctuation in the shear force applied to the buttocks by measuring the shear and normal forces applied to the buttocks and back support, and to contribute to the prevention of decubitus ulcers in those who sit in wheelchairs with a reclining back support.

Methods

Study design

This study design was experimental study. This study was conducted with the approval of the Research

Ethics Committee at the Kawasaki University of Medical Welfare (# 074); informed consent was obtained from all subjects.

Subjects

The subjects were 11 healthy adult men without leg or trunk diseases (age: 22.0 SD 5.2 years, height: 171.1 SD 5.9 cm, and body weight: 66.1 SD 6.6 kg).

Measurements of forces applied to buttocks and back support

The amount of force applied to the buttocks was measured by using a force plate (Kyowa Electronic Instruments Co., Ltd., Japan, K07-1712) to measure the reaction force in the posterior direction as the shear force in the anterior direction. The sampling frequency was 100 Hz. A pressure and shear force sensor (Molten Corp., Japan, Predia) was used to measure the timing of the force applied to the back support. This sensor measured the pressure using air displacement and measured the shear force with a strain gauge; it is made of flexible plastic and is elliptical in shape. It measured pressures over a range of 0 to 200 mmHg and shear force between 0 and 50 N [10]. This sensor was attached to the back at the location of greatest pressure from the back support during comfortable sitting on the experimental chair. The shear force measured by this sensor is positive for the force downward from the trunk to the back support and negative for the upward force.

In this study, we used an experimental chair with an electrical function for reclining the back support (Hashimoto Artificial Limb Manufacturer Co., 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 back support reclines: 3°/s. The measurement posture was a comfortable sitting posture on the force plate on the experimental chair. In addition, to achieve a constant friction between the seat and the clothing, all subjects wore the same clothing material which was 100% cotton. In the present study, the buttocks were positioned so that the distance from the back support to the pelvis in the measurement posture was 3 cm [11]. To reduce the effect of differences in the position of the lower extremities, the thigh angle was adjusted in the horizontal plane elevating the feet by stacking wooden boards under the experimental chair [12], and the position of the feet was adjusted so that the lower leg formed a line perpendicular to the feet [13]. Furthermore, to reduce the resistance of the lower extremities, a roller board was placed under the feet. In addition, participants were instructed to fold their arms in front of the chest in a relaxed state and not to voluntarily change the body position during the experiment. Head support was not used in order to achieve reproducibility (figure 1). To consider the influence of the collapse in a subject's posture during the amount of time needed to make the measurements, the measurements were taken 10 s after the posture was set. The experimental back support was reclined at increasing angles beginning in a full upright position of 10° from the vertical (initial upright position: IUP), proceeding to a fully reclined position (FRP) of 40° from the vertical, and subsequently returning to an upright position (RUP). The time required to measure the forces was 5 s in the IUP, 10 s in the FRP, and 5 s in the RUP. This study had three experimental conditions: the IUP, FRP, and RUP. In each positions, we adopted an average values which measured stable 201 samples for each subjects.

figure 1

Statistical analyses

The measured shear and normal forces were normalized by the body weight [percent body weight; %BW] to consider the effect of body weight. To investigate the mechanism for the fluctuation in the shear force applied to the buttocks by reclining the back support, the shear and normal forces in the three experimental conditions was compared. For statistical analysis, the one-way analysis of variance

(ANOVA) and the Bonferroni multiple comparison test were used with the level of significance identified as $p < 0.05$. The statistical analyses were performed using the Statistical Package for the Social Sciences (SPSS) ver. 16.0J for Windows. In addition, we analysed the fluctuation pattern of the forces applied to the buttocks and back support.

Results

Table 1 shows the measured shear and normal forces applied to the buttocks, and figure 2 shows the wave representing the fluctuation pattern of these forces on the typical example.

table 1

figure 2

The average value of the shear force applied to the buttocks was 9.4 SD 2.4 [%BW] in the IUP, 9.3 SD 1.2 [%BW] in the FRP, and 15.0 SD 2.9 [%BW] in the RUP. Significant differences appeared between the RUP and the other positions. There was not significant comparison between the IUP and FRP. The average value of the normal force applied to the buttocks was 78.0 SD 5.0 [%BW] in the IUP, 66.0 SD 8.2 [%BW] in the FRP, and 87.0 SD 6.9 [%BW] in the RUP. The three positions differed significantly.

The fluctuation patterns of the measured forces are described below. The fluctuation pattern of the measurements value showed a similar pattern in all subjects. The shear force in the anterior direction applied to the buttocks showed no significant change from the IUP to the FRP. Subsequently, this force showed a peak value in the middle phase, a back support angle of 20° to 30°, while returning to the RUP. The value of this force was higher in the RUP than in the IUP. Regarding the forces applied to the back support, the shear force downward increased gradually from the IUP to the FRP. The shear force downward decreased and the normal force increased in proportion to the extent of the return to the upright position from the FRP until the middle phase. Thereafter, the shear force suddenly became directed upward in the terminal phase, a back support angle of 15°, of the return to the upright position, and the normal force continued to increase until the RUP.

Discussion

In this study, the mechanism of the fluctuation in the shear force applied to the buttocks 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 resulting fluctuation pattern of the measured forces applied to the back support showed that the shear force downward decreased and the normal force increased in proportion to the extent of the return to the upright position of the back support from the FRP until the middle phase (an angle of about 20°–30° from the vertical). Thereafter, the shear force suddenly became upward in the terminal phase (15° from the vertical), and the normal force continued to increase until the RUP. The fluctuation pattern of the shear force in the anterior direction applied to the buttocks showed a peak value in the middle phase as defined for the fluctuation in the forces applied to the back support, and the value of this force was higher in the RUP than in the IUP. The timing of this fluctuation in the measured forces suggests that the fluctuation in the force applied to the back support significantly influences that applied to the buttocks. The normal force is vertical to a surface, and the shear force is parallel. If the trunk and pelvis were inclined with the back support as it reclined while remaining parallel to it, the primary force applied to the back support should be the normal force because the head, trunk, pelvis, and arms are supported by the surface of the seat. Therefore, the observed fluctuation in the shear force applied to the back support showed that the inclination of the trunk and pelvis did not parallel that of the back support as it reclined. The wheelchair users' trunk and pelvis were inclined around the hip joint as the axis of rotation as the back support reclined. On the other hand, the axis of rotation of the back support is more than 10 cm behind the hip joint. These facts motivate the hypothesis that the shear force applied to the buttocks increases with the difference between the positions of the axes of rotation of the back support and the trunk–pelvis. We discuss the results of the present study on the basis of this hypothesis below.

In the results of this study, the shear force applied to the buttocks in the RUP was significant higher than that in the other positions. This result was different in the FRP and the same in the RUP as that of the previous study by Gilsdorf *et al.* [8], which found that a shear force occurred in the posterior direction in the FRP and in the anterior direction in the RUP. In the FRP, we could guess that the trunk slides downward relative to the back support because of the shear force downward applied to the back support. According to the action–reaction law, the shear force downward applied to the back support is a reaction to the support of the trunk–pelvis as the back support reclines. Thus, it was considered that the shear force in the posterior direction occurred in the previous study of Gilsdorf *et al.* [8], which compared the forces with no cushion and with two types of cushion. This previous study found that the shear force in the posterior direction did not differ significantly among these three conditions in the FRP, suggesting that the chair seat conditions did not affect this force. Therefore, in the present study, the absence of the shear force in the posterior direction, in contrast to the results of the previous study [8], is attributed to the low friction coefficient between the material on the surface of the back support and the material of the clothing worn by the subjects.

The present study showed that the shear force in the anterior direction applied to the buttocks in the RUP was significantly higher than in the IUP. The distance between the axes of rotation of the back support and the trunk–pelvis was lengthened by sliding the trunk downward relative to the back support as the back support reclined. This suggests that the primary factor of the greater increase in the shear force in the anterior direction in the RUP was the greater difference between the directions of the forces applied to the back-support and the rotation direction of the trunk–pelvis. In the present study, performed upon able-bodied subjects, unconscious postural muscle activity might have played a role in the lack of sliding. Nevertheless, the shear force applied to the buttocks in the RUP increased by more than 5 [%BW] compared with that in the IUP. Hobson [14] reported that a back support recline angle of 30° caused a 25% increase in the surface shear force compared with a recline angle of 10° for subjects with spinal cord injuries. In addition, Bennett *et al.* [15] compared the shear and normal forces applied to the buttocks of normal and paraplegic subjects. They found that the normal force did not differ significantly between the two groups of subjects. However, the shear forces for sitting paraplegic subjects were roughly 3 times those of the normal subjects, and the rate of pulsatile skin blood flow volumes applied to the buttocks in sitting paraplegic subjects were only one-third of those of comparable normal subjects. In addition, in the present study, the normal force in the RUP exhibited an increase of roughly 10 [%BW] compared with the normal force in the IUP, because of the reaction force downward to the shear force applied to the buttocks, which suddenly became upward in the terminal phase of returning to the upright position of the back support. A shear force can exist only when two surfaces are pressed against each other. This maximum shear force just before sliding occurs is defined by:

$$F_{shear, max} = f * F_N$$

where f is the friction coefficient and F_N is the normal force. This implies that in regions where the pressure is relatively high, the shear force can become high as well [5]. These considerations suggest that the release of the remaining shear force applied to the buttocks and back support when the back support was reclined by wheelchair users who cannot modify their posture by themselves is important for the prevention of decubitus ulcers.

Regarding a method of releasing the shear force, Gilsdorf *et al.* [8] reported that leaning forward away from the back support caused the shear force applied to the buttocks to return to values close to those at the IUP after back support elevation. In addition, Van Geffen *et al.* [16] reported that a combination of independent pelvis rotation and seat inclination is effective for regulating the net buttock shear force and the sacral interface pressure. Furthermore, Goossens *et al.* [5] stated that the local shear forces can be affected by the choice of cushion material and by tilting the seat and changing the angle of the back support. To prevent decubitus ulcers from occurring in the sitting posture on a chair in this manner, strategies for obtaining various angles of the seat and/or back support are necessary. In addition, we suggest that adjusting the position of the axis of rotation of the back support be included as a strategy for reclining wheelchair use on the basis of the results of the present study. However, we did not investigate this hypothesis, which was motivated by the fluctuation pattern of the measurement forces (i.e. an increase in the shear force applied to the buttocks because of the difference between the positions of the axes of rotation of the back support and trunk–pelvis). In the future, we plan to inspect this hypothesis and put it to practical use.

Limitation

The limitation of this study was that the subjects were healthy male. Therefore, it is difficult to adapt the result of this study to all wheelchair users. Future studies should investigate the mechanism of the fluctuation in the shear force applied to the buttocks of wheelchair users.

Conclusion

The purpose of this study was to investigate the mechanism of the fluctuation in the shear force applied to the buttocks by measuring the shear and normal forces applied to the buttocks and back support, and to contribute to the prevention of decubitus ulcers in those who sit in wheelchairs with a reclining back support. In the results of this study, the shear force applied to the buttocks in the RUP was significant higher than that in the other positions. The results of this study suggested that the adjustment of the axes of rotation of the back support and trunk–pelvis and the release of the remaining shear force after the back support is reclined are important for the prevention of decubitus ulcers.

Acknowledgement

This study was supported by a grant-in-aid from the 2010 Kawasaki University of Medical Welfare's expense budget for medical welfare study and research.

Declaration of interest

The authors report no conflicts of interest.

References

[1] Reenalda J, Jannink M, Nederhand M, Ijzerman M. Clinical use of interface pressure to predict pressure ulcer development: A systematic review. Assistive Technology 2009; 21: 76-85.

[2] Dinddale SM. Decubitus Ulcers: Role of Pressure and friction in causation. Arch Phys Med Rehab 1974; 55: 147-152.

[3] Bennett L, Kavner D, Lee BK, Trainor FA. Shear vs pressure as causative factors in skin blood flow occlusion. Arch Phys Med Rehabil 1979; 60: 309-314.

[4] Sakuta Y, Takahashi M. The interaction between pressure and shear force as a factor of pressure ulcers by assessing blood flow measurement [in Japanese]. JSMBE 2006; 44: 101-106.

[5] Goossens RHM, Snijders CJ, Holscher TG, Heerens WC, Holman AE. Shear stress measured on beds and wheelchairs. Scand J Rehab Med 1997; 29: 131-136.

[6] Trefler E, Hobson DA, Taylor SJ, Monahan LC, Shaw CG. Seating and mobility for person with physical disabilities. Therapy Skill Builders, Memphis, 1993, pp.3-5.

[7] Kurihara T, Kinose T, Ohtsu K, Okuyama N, Sakai Y. A study of relation between pressure sores and seating positioning ability in wheelchair use by elderly people [in Japanese]. J.T.H.S 2003; 5: 258-262.

[8] Gilsdorf P, Patterson R, Fisher S, Appel N. Sitting forces and wheelchair mechanics. J Rehab Res Dev 1990; 27: 239-246.

[9] Kobara K, Eguchi A, Fujita D, Nishimoto T, Ishiura Y, Watanabe S. Initial mechanism of shear in comfortable sitting on a chair - Examination by the time element of displacement of seat pressure distribution - [in Japanese]. Rigakuryoho Kagaku 2007; 22:185-188.

[10] Akins JS, Karg PE, Brienza DM. Interfase shear and pressure characteristics of wheelchair seat cushions. J Rehab Res Dev 2011; 48: 225-234.

[11] Kobara K, Shinkoda K, Watanabe S, Eguchi A, Fujita D, Nishimoto T. Investigation of validity of model for estimating shear force applied to buttocks in elderly people with kyphosis while sitting comfortably on a chair. Disabil Rehabil Assist Technol. 2011; 6: 299-304.

[12] Kobara K, Shinkoda K, Eguchi A, Watanabe S, Fujita D, Nishimoto T. Influence of thigh angle from a level on shear force and normal force occurred under the buttocks of subjects sitting comfortably on a chair [in Japanese]. Nihon Gishi Sogu Gakkaishi 2009; 25: 108-110.

[13] Kobara K, Eguchi A, Watanabe S, Shinkoda K. The influence of distance between the backrest of a chair and the position of the pelvis on maximum pressure of the ischium and estimated shear force. Disabil Rehabil Assist Technol.

2008; 3: 285-291.

[14] Hobson DA. Comparative effects of posture on pressure and shear at the body-seat interfase. J Rehab Res Dev 1992; 29: 21-31.

[15] Bennett L, Kavner D, Lee BY, Trainor FS, Lewis JM. Skin stress and bloodflow in sitting paraplegic patients. Arch Phys Med Rehabil 1984; 65: 186-190.

[16] Van Geffen P, Reenalda J, Veltink PH, Koopman BFJM. Effects of sagittal postual adjustments on seat reaction load. J Biomech 2008; 41: 2237-2245.

Figure legends

figure 1. Measurement posture (the initial upright position)

a. 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), b. level goniometer, c. personal computer, d. data logger, e. Predia, f. force plate, g. roller board

table 1. Shear and normal forces at various back angles

a: the RUP vs IUP and vs FRP: $p < 0.05$, IUP vs FRP: not significant

b: the IUP vs FRP, the FRP vs RUP: $p < 0.01$, the IUP vs RUP: $p < 0.05$

figure 2. The wave of the fluctuation pattern of the forces (the typical example)

A. The forces applied to buttocks

B. The forces applied to back support