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Original Article

Development of an algorithm to predict comfort of wheelchair fit based on clinical measures

Keisuke Kon, PO, PhD[1)]*, Yasuyuki Hayakawa, PO, PhD[1)], Shingo Shimizu, PT, PO[1)], Toshiya Nosaka, PO, PhD[1)], Takeshi Tsuruga, ENG, PhD[1)], Hiroyuki Matsubara, PO[1)], Tomohiro Nomura, PO[1)], Shin Murahara, PO[1)], Hirokazu Haruna, PT, PhD[2)], Takumi Ino, PT[2)], Jun Inagaki, ENG, PhD[3)], Toshiki Kobayashi, PO, PhD[1)]

[1)] *Department of Prosthetics and Orthotics, Faculty of Health Sciences, Hokkaido University of Science: 7-15-4-1 Maeda, Teine, Sapporo, Hokkaido 006-8585, Japan*
[2)] *Department of Physical Therapy, Faculty of Health Sciences, Hokkaido University of Science, Japan*
[3)] *Department of Information Engineering, Faculty of Engineering, Hokkaido University of Science, Japan*

Abstract. [Purpose] The purpose of this study was to develop an algorithm to predict the comfort of a subject seated in a wheelchair, based on common clinical measurements and without depending on verbal communication. [Subjects] Twenty healthy males (mean age: 21.5 ± 2 years; height: 171 ± 4.3 cm; weight: 56 ± 12.3 kg) participated in this study. [Methods] Each experimental session lasted for 60 min. The clinical measurements were obtained under 4 conditions (good posture, with and without a cushion; bad posture, with and without a cushion). Multiple regression analysis was performed to determine the relationship between a visual analogue scale and exercise physiology parameters (respiratory and metabolism), autonomic nervous parameters (heart rate, blood pressure, and salivary amylase level), and 3D-coordinate posture parameters (good or bad posture). [Results] For the equation (algorithm) to predict the visual analogue scale score, the adjusted multiple correlation coefficient was 0.72, the residual standard deviation was 1.2, and the prediction error was 12%. [Conclusion] The algorithm developed in this study could predict the comfort of healthy male seated in a wheelchair with 72% accuracy.

Key words: Wheelchair seating, Posture maintenance, Multivariate analysis

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INTRODUCTION

In Japan's rapidly aging society, approximately 80% of individuals in elderly care facilities use a wheelchair for mobility and everyday activities. However, most of the wheelchairs used in elderly care facilities are of the standard type (conveyance devices) with minimal functions. These wheelchairs are not suitable for long-term use, and as shown in Fig. 1-A, they can contribute to poor posture. In addition, because the Japanese Industrial Standards for currently used wheelchairs are based on North American standards, these wheelchairs are too big and not suitable for the physical dimensions of the smaller Japanese elderly who are often on the verge of falling when seated in these wheelchairs (Fig. 1-B). Sekikawa[1)] reported that little attention is paid to the "wheelchair fit" for individual users, because a wheelchair is generally considered as merely a device for mobility.

Sugihara et al.[2)] described "falling" as a risk factor in elderly individuals who use wheelchairs. Among wheelchair users, a common reason for falls is a change in body position[3)]. Being seated for long periods in a poorly fitted wheelchair could lead to excessive stress[4)], and frequent changes in body position could lead to falls and injuries.

Holmes et al.[5)] classifies stress into "distress," which has adverse effects on the body, and "eustress," which is associated with a moderate feeling of tension. These stresses affect the autonomic nervous system (ANS)[5, 6)], and unconscious reflexive responses[7)] presumably occur to avoid distress. Previous studies[6–12)] have shown the effect of emotions on ANS functions including heart rate and respiration. Therefore, wheelchair comfort is likely correlated with these ANS parameters.

Caregivers may discuss comfort with wheelchair users and adjust their wheelchair positioning (Fig. 1-C) to promote comfort with a moderate amount of tension in order to reduce the risk of falls. Recent research in postural maintenance has included posture adjustment and prevention of pressure ulcers based on seating pressures[13–15)] and the adjustment of backrest angles[16–18)]. Comfort can be assessed if communication between the caregiver and wheelchair user is smooth, but in elderly persons with dementia or a speech impairment, obtaining this information depends on the caregiver's experience. Therefore, the purpose of the present study was to develop an algorithm that can predict the comfort of a subject using a wheelchair, based on common clinical measurements and without depending on verbal

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*Corresponding author. Keisuke Kon (E-mail: kon@hus.ac.jp) communication.

SUBJECTS AND METHODS

Twenty healthy males (mean age: 21.5 ± 2 years; height: 171 ± 4.3 cm; weight: 56 ± 12.3 kg) participated in this study.

Comfort was evaluated every 5 min from the start of testing using a visual analogue scale (VAS) for obtaining information from the subjects. This VAS was a 10 cm line on which 0 cm represented a state of relaxation, as when going to sleep, and 10 cm represented the worst discomfort experienced previously.

Posture quality (good or poor) was evaluated by the vertical component of a force plate (BP400600HF, AMTI, Watertown, NY, USA). A good posture was defined as one in which the center of gravity of the head, arms, and trunk (HAT) segment and the sitting center of pressure were aligned, while a poor posture was defined as one with an inclined ground reaction force vector.

The pelvic tilt angle is used to identify a posterior pelvic tilt, or the so-called sacral sitting, which occurs with poor posture. In addition, several markers were attached to the body, and thoracoabdominal breathing was recorded using 14 infrared cameras (MX-T10S, VICON, Oxford, UK) and a 3D motion analysis system (VICON-Nexus1.82, VICON, Oxford, UK).

To acquire exercise physiology data, a respiratory and metabolic analysis system (k4b2, COSMED, Rome, Italy) was attached to each subject, and parameters such as energy consumption, respiratory rate, and ventilation amount were measured. To acquire ANS data, a heart rate monitor (HRV-LIVE, Biocom, Warren, MI, USA) was attached. In addition to assessment of the increase in heart rate, a frequency analysis of the heart rate data over 256 points was performed, and the sympathetic and parasympathetic nervous system components were determined. A sphygmomanometer (HEM-7500F, OMRON, Kyoto, Japan) was used to measure systolic and diastolic blood pressures. In addition, salivary amylase activity was measured using a salivary amylase monitor (T-110-N, NIPRO, Tokyo, Japan), and the percentage change was used as an indicator of sympathetic nervous system activity and as a stress marker.

Verbal instructions such as “Do not move after starting until the experiment is complete” were given to each subject. Each subject underwent testing under 4 experimental conditions (Table 1). These were good posture without a cushion as “non-cushion good (NCG)” and with a cushion as “cushion good (CG)”, and bad posture without a cushion as “non-cushion bad (NCB)” and with a cushion as “cushion bad (CB)”. The experimental wheelchairs were built from standard wheelchairs so that the seat height, footrest height, and reclining angle could be adjusted for each subject.

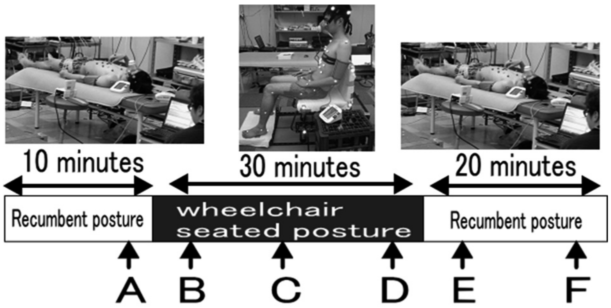
To assess the effects of a standard cushion and those of a high-performance cushion, 2 types of cushions were used in the experiment: a J2 cushion (J2:JFUSION1414, Access International, Tokyo, Japan) and a wheelchair cushion (FlatFit, JCI, Sendai, Japan). All subjects were assessed using both cushions. The subjects were divided into 2 groups to assess the differences in the effects of the 2 cushions. The J2 cushions are generally perceived as high-end products, while the FlatFit cushion is considered a popular price product. Figure 2 summarizes the experimental protocol. This was a single system design, with the first 10 min in the recumbent resting position as the baseline and the next 30 min in the sitting position, which was followed again by the recumbent resting posture.

A: Too large wheelchair B: Posture of a patient about to fall from a wheelchair C: Posture of a patient seated stably in a wheelchair

Fig. 1. Issues related to wheelchair fit

Table 1. Experimental conditions

Experimental level	Notation	Conditions
A1	NCG (Non-Cushion Good Posture)	Good posture, no cushion
A2	CG (Cushion Good Posture)	Good posture, with cushion
B1	NCB (Non-Cushion Bad Posture)	Bad posture, no cushion
B2	CB (Cushion Bad posture)	Bad posture, with cushion



A: 7 minutes before end of rest
B: 5–10 minutes in the seated posture
C: 15–20 minutes in the seated posture
D: 25–30 minutes in the seated posture
E: 10 minutes after start of rest
F: 15–20 minutes after start of rest

Fig. 2. Experimental procedure

The data were obtained consecutively after the start of the experiment. The evaluated parameters were extracted for the time points from A to F (Fig. 2) for data analysis. The VAS score was used as an objective variable, and the other evaluation parameters were used as explanatory variables for multiple regression analysis, which was performed using a statistical analysis software (JUSE-StatWorks V5, The Institute of Japanese Union of Scientists & Engineers, Tokyo Japan).

Table 2. Regression formula to predict VAS

	Variables	Standard regression coefficient
x1	Systolic blood pressure**	−0.066
x2	HF (High Frequency) component**	−0.0014
x3	Respiratory rate	−0.134
x4	LF/HF (Low Frequency / High Frequency) component**	−0.299
x5	Heart rate increase rate**	−0.046
x6	Ventilation amount**	−1.404
x7	Amylase elevation rate**	−0.002
x8	Posture (good posture 1, poor posture 2)**	0.983
x9	Measurement time (minutes)**	0.077
x10	With/without cushion (with 1, without 2)**	1.853
x11	Heart rate**	0.116
b	Constant term	9.389

**: $p < 0.01$. Multiple correlation coefficient adjusted for the degrees of freedom: $R^2 = 0.72$.
Residual standard deviation = 1.2

This study underwent ethical review and received approval from the Hokkaido University of Science, and written informed consent was obtained from each subject.

RESULTS

A regression formula is shown for predicting the VAS score as the objective variable (Table 2). The actual measurement value of each parameter is substituted for each variable (x1–x11) in Table 2, multiplied by the partial regression coefficient, and all the variables are then added, including a constant term (b), to predict the VAS score. The regression formula is shown below.

$$\text{Predicted VAS} = 9.389-(0.066*x1)-(0.0014*x2)-(0.134*x3)$$
$$-(0.299*x4)-(0.046*x5)-(1.404*x6)-(0.002*x7)$$
$$+(0.983*x8)+(0.077*x9)+(1.853*x10)+(0.116*x11)$$

For example, during sitting; x1: systolic blood pressure is 140 mmHg, x2: HF (High Frequency) component (parasympathetic nervous system component) is 500 ms, x3: respiratory rate is 14/min, x4: LF/HF (Low Frequency/HF) ratio is 1.2, x5: rate of increase in heart rate(rate of increase with value at rest as baseline) is 120%, x6: ventilation amount is 0.5 L/min, x7: amylase elevation rate (rate of increase from value at rest as baseline) is 100%, x8: posture is good posture 1, x9: measurement time is 15 min, x10: without cushion condition is 2, and x11: heart rate is 75 beats/min; then, by substituting these variables in the formula:

$$\text{Predicted VAS} = 9.389-(0.066*140\ \text{mmHg})-(0.0014*500\text{ms})$$
$$-(0.134*14/\text{min.})-(0.299*1.2\ \text{ratio})-(0.046*120\%)$$
$$-(1.404*0.5\ \text{l})-(0.002*100\%)+(0.983*1)+(0.077*15\ \text{min.})$$
$$+(1.853*2)+(0.116*75\ \text{beats/min.}) = 5.15$$

The adjusted multiple correlation coefficient, which shows the accuracy of the regression formula, was 0.72 (Table 2).

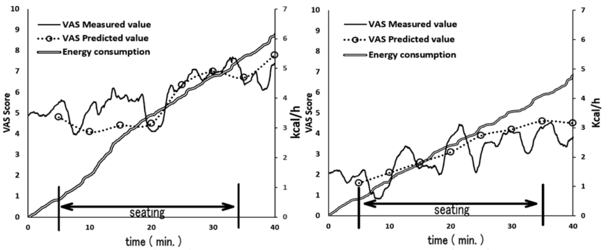
Figure 3 shows the graph for subject A (worst fit) and subject X (best fit) during the NCB and CB conditions. The horizontal axis is the time; the left vertical axis shows the VAS score; and the right vertical axis shows energy consumption based on respiratory and metabolic analyses. The results demonstrated that the predicted VAS varied greatly and did not completely correspond with the actual measurement values in subject A (Fig. 3-A, B). However, subject X showed a very good fit (Fig. 3-C, D).

DISCUSSION

The purpose of the present study was to predict the comfort of a subject seated in a wheelchair, based on common clinical measurements and without depending on verbal communication for subjective comfort assessment. It was found that in healthy adult male, wheelchair comfort could be predicted with an accuracy of 72%. However, caution is needed for a VAS score of 7.6, when using this algorithm. This algorithm, which predicts comfort based on wheelchair-seated postural data and ANS parameters, is necessary so that caregivers can adjust the wheelchair-seated posture of patients who cannot communicate well conveniently and objectively.

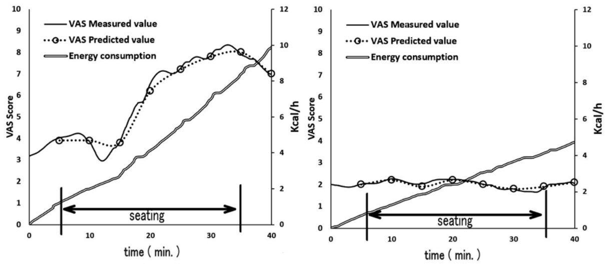
The present study results showed that in healthy male, the VAS score could be predicted with an accuracy of 72%. The residual standard deviation was 1.2. For example, for a predicted VAS score of 7.6, there is a variation of 1.2. Statistically, this indicates that 95% of the data fall within the mean ± 2 SD, so that if the predicted value exceeds 7.6, there is a 2.5% possibility that the actual VAS score is the maximum possible value of 10. Therefore, when utilizing this algorithm measurement system to predict the comfort of a wheelchair fit, caregivers should be cautioned when the predicted value exceeds 7.6.

In a similar study, to validate the prediction accuracy, Huang et al.19) performed regression analysis using the VAS score as the dependent variable and the ratio of the lumbar multifidus muscle cross-sectional area of the unaffected and affected sides as an independent variable to predict the



A: NCB (subject A)

B: CG (subject A)



C: NCB (subject X)

D: CG (subject X)

Fig. 3. Predicted VAS score and actual VAS score over time in subject A (worst fit) and subject X (best fit)
Dotted line: energy consumption measured values
Solid line: VAS predicted value, dotted line: VAS measured value
The right vertical axis: energy consumption (kcal/h) of cumulative per one hour
The left vertical axis: VAS scores (maximum pain 10 points)
CG: cushion good posture; NCB: non-cushion bad posture; VAS: visual analogue scale

severity of chronic lower back pain. For the prediction accuracy, they reported a coefficient of determination of 0.72 and a standard deviation of 1.24. Thus, with regard to prediction accuracy and variation, similar results were found, even though the measurement conditions were different.

Watanuki et al.[20] attempted to create an estimation model using discriminant analysis, with psychological excitement (VAS) when watching television programs as a dependent variable and ANS parameters such as blood pressure and heart rate as independent variables. They reported a distinction rate of 83% for the "calm" condition and a mean error of 17%. In the present study, the residual standard deviation for the VAS (range 0–10) was 1.2; in other words, the prediction error was 12%. This is similar to the prediction accuracy reported by Watatuki et al[20].

Figure 3 shows the serial changes in the predicted VAS in subject A. During the NCB condition, compared to the CG condition, when the energy consumption was higher, the measured VAS was also higher. The predicted VAS was also higher during the NCB condition; therefore, identifying a difference, exceeding an error of 12%, would be possible.

The present study did not include elderly patients because of ethical considerations. Therefore, the findings should be confirmed in this population with further investigation. Our research group is currently focusing on development of a wheelchair fit support system using Kinect 2 for Windows (Kinect 2). Kinect 2 acquires body skeletal coordinate data, so that posture can be assessed with a camera recording the wheelchair-seated posture. Moreover, with image processing technology, the heart rate and respiratory data can be obtained from Kinect 2 without any contact. By combining the present algorithm for predicting wheelchair comfort, as established in this study, with a wheelchair fit support system using Kinect 2, appropriate guidelines, necessary precautions, and other important information could easily be provided to the caregivers of wheelchair patients.

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