A Validation Test of Using Shoulder Joint Moment in Evaluation of Load in Wheelchair Propulsion

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Abstract— **Manual wheelchair is an effective device for assisting independent life of motor disabled subjects. However, many users of manual wheelchair have been suffered from shoulder pain because propelling the wheelchair needs repetitive movement of upper extremities. The purpose of this study was to examine a validity of using shoulder joint moment in evaluation of load on the users in wheelchair propulsion. Since shoulder joint moment can evaluate mechanical load on the shoulder, the indexes are expected to provide information to help wheelchair propulsion in decreasing of shoulder pain. Two evaluation indexes derived from shoulder joint moment were tested in this paper: F_T/M_S and F_R/M_S, which showed contribution of shoulder joint moment (M_S) to wheelchair propulsion (tangential force on handrim F_T) and to the resultant force on handrim (F_R). These indexes were compared to the index F_T/F_R which was based on previous studies. Measurements of movements during wheelchair propulsion were performed with 3 healthy subjects on stationary wheelchair ergometer under the different conditions of propulsion speed and resistance of ergometer. Correlation coefficient between the proposed indexes and F_T/F_R were low (-0.51 to 0.10), which suggested that the proposed indexes had different information from the index F_T/F_R. Change of the index values between low and high propulsion load conditions were different between subjects. These results suggest that using indexes derived from shoulder joint moment would be effective in evaluation of load in wheelchair propulsion.**

I. INTRODUCTION

A wheelchair is the assistive device that has been widely used by persons with lower limb disability. Manual wheelchair is effective for assisting independent life of such subjects, since it can be propelled by only the power of user and it has high portability. However, propelling the wheelchair needs repetitive movement of upper extremities, by which many users have been suffered from shoulder pain [1, 2]. Based on the study that shoulder pain intensity was inversely related to subjective quality of life (QOL) and physical activity [3], reducing shoulder pain is considered to be effective to improve QOL of wheelchair users.

Estimation of shoulder joint moment during wheelchair propulsion was used in evaluation of demand on the upper extremities [4]. Since joint moment estimation during movements has been used for evaluations of motor function or movements, joint moment of upper limbs may be used for evaluation of loads on upper limbs during wheelchair propulsion, or for the evaluation of the risk of shoulder pain. Although shoulder joint moment value itself is effective for evaluation of the load on the shoulder of wheelchair users, it is difficult to decrease shoulder joint moment in some cases such as fast speed running or running on slope. Therefore, it would be effective to use joint moment value as an index of contribution of generated moment to wheelchair propulsion.

An index based on the ratio of tangential force (F_T) to resultant force (F_R) on the handrim was used for evaluation of effective force in wheelchair propulsion or of movement patterns of wheelchair propulsion [5, 6]. The index F_T/F_R is considered to evaluate contribution of applied force to propelling wheelchair. However, the index can not evaluate directly the load on the shoulder such as generated moment during wheelchair propulsion. Therefore, the purpose of this study was to examine evaluation index derived from shoulder joint moment in order to evaluate the load on the shoulder joint during wheelchair propulsion. In this paper, two indexes derived from shoulder joint moment were tested in comparing to the index F_T/F_R in manual wheelchair propulsion.

II. METHODS

A. *Estimation of Shoulder Joint Moment*

In this paper, the shoulder joint moment was estimated by solving the Euler-Newton equation which represents translational motion and rotational motion of rigid body in the sagittal plane assuming for simplicity that propulsion movement is mainly performed in the sagittal plane. The motion equations (Eqs. (1)-(3)) were solved in the order from the hand to the upper arm.

$$m_i \ddot{X}_{G_i} = F_{x_i} - F_{x_{i+1}} \tag{1}$$

$$m_i \ddot{Y}_{G_i} = F_{y_i} - F_{y_{i+1}} - m_i g \tag{2}$$

$$\begin{aligned} I_i \ddot{\theta}_i = M_i - M_{i+1} &+ \left(r_i F_{x_i} + (1 - r_i) F_{x_{i+1}}\right) l_i \sin\theta_i \\ &- \left(r_i F_{y_i} + (1 - r_i) F_{y_{i+1}}\right) l_i \cos\theta_i \end{aligned} \tag{3}$$

where *i* shows segment number. Body segment parameters, m_i, l_i, r_i and I_i, are segment mass, segment length, center of mass (CoM) position ratio from the distal end and moment of inertia, respectively. M_i and F_{x_i} and F_{y_i} are joint moment and joint reaction forces, respectively. X_{G_i} and Y_{G_i} show segment CoM position in the sagittal plane. θ_i is inclination angle and g shows gravitational acceleration. Body segment parameters were referred from previous studies [7, 8].

Kinematics information such as segment inclination angle was calculated from the segment vector which represents segment orientation. Considering joint moment estimation under the practical condition with wearable measurement system, the segment vector was calculated by quaternion method from acceleration and angular velocity signals

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measured with inertial sensors [9]. Joint moment estimation using measured data with inertial sensors has been shown to be practical [10]. In this study, inertial sensor was attached to around the CoM position of each segment, and measured acceleration signals were used in the motion equations as CoM acceleration of the segment that the sensor was attached. Since the CoM acceleration is expressed in the global coordinate system (GCS), acceleration signals measured in the sensor coordinate system (SCS) were converted to the values in the GCS by using orientation of sensor that was calculated by the quaternion method using data measured with inertial sensor.

B. *Evaluation Indexes in Wheelchair Propulsion*

In order to evaluate the load on the shoulder joint, two indexes derived from shoulder joint moment (M_S) were tested. One of them was the ratio of the tangential force applied on the handrim to shoulder joint moment (F_T/M_S). This means contribution of shoulder joint moment to wheelchair propulsion. The other is the ratio F_R/M_S. This means contribution of shoulder joint moment to the force on the handrim. These indexes were calculated from peak values of F_T, F_R and M_S in each propulsion cycle. Each propulsion cycle was detected from measured data by using F_T [11]. F_T and F_R were normalized by body weight (BW) of subject and M_S was normalized by BW and height of subject.

III. EXPERIMENTAL TEST

A. Method

Three able bodied subjects (non-wheelchair users) participated in measurements after getting the consent from them. They propelled a wheelchair on stationary wheelchair ergometer as shown in Fig. 1. The force applied on the handrim was measured with SmartWheel (Out-Front) [12] which was mounted to the left side of the wheelchair. Inertial sensors (MTw, Xsens Technologies B.V.) were attached on the hand, the forearm, and the upper arm of the left side of body, and the trunk with stretch band. An inertial sensor was also attached to the SmartWheel with double-sided tape in order to perform time synchronization between inertial sensors and SmartWheel by detecting a threshold value of cycling speed. Sampling frequencies were 240 Hz and 75 Hz for the SmartWheel and inertial sensors, respectively. Therefore, both data were resampled to 1200 Hz after measurements.

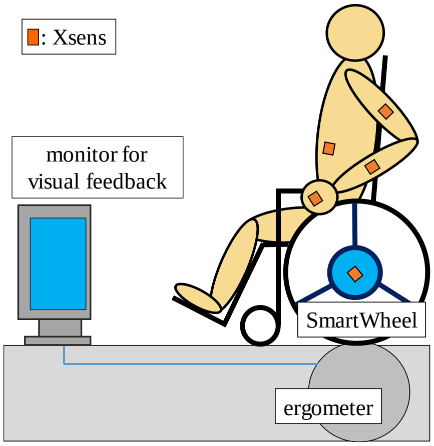


Fig.1 Experimental setup.

Measurements were performed under the conditions of 3 propulsion speeds (0.3 m/s as slow, 0.5 m/s as moderate, and 0.7 m/s as fast) and 3 ergometer rolling resistances (low, moderate, and high). The propulsion speeds were determined based on studies of wheelchair propulsion speeds in daily activity [13, 14]. The values of rolling resistance were determined based on 2 additional measurements. First, resultant force F_R were measured during wheelchair propulsion on level floor, 6.0% slope and 12% slope. From the results, value of high resistance was determined to be less than average peak value of F_R in wheelchair propulsion on the 12% slope, which was 21.13±3.10 %BW. Then, the rolling resistance of the ergometer system were adjusted by measuring F_R under the condition of 0.5 m/s of running speed.

The order of the measurement condition was from slow speed to fast speed and from low resistance to high resistance, that is, slow speed-low resistance, moderate speed-low resistance, fast speed-low resistance, slow speed-moderate resistance, and finally fast speed-high resistance. Considering subject’s fatigue, 5 minutes rest was taken when the rolling resistance was changed. Propulsion speeds was adjusted by subjects themselves through visual feedback of speed obtained from ergometer. Subjects performed 25 strokes in each trial. The first and the second strokes were excluded from analysis since they were in a period for acceleration, and 20 strokes from the third stroke were analyzed.

B. Results

First, estimated shoulder joint moment using inertial sensor was compared to those values estimated with 3D motion measurement system in a preliminary experiment. Examples of estimated shoulder joint moments are shown in Fig. 2. These estimated moments showed high correlation coefficients (about 0.9).

Average peak values of estimated shoulder joint moment were shown in Fig. 3. The moment increased as the propulsion speed increased and also as rolling resistance increased.

The relationships between the proposed indexes and the ratio F_T/F_R based on the previous study are shown in Fig. 4. There was no significant correlation between those indexes. Correlation coefficient between F_T/M_S and F_T/F_R of each subject was from -0.001 to 0.10, and that between F_R/M_S and F_T/F_R was from -0.51 to -0.15 as shown in Table 1.

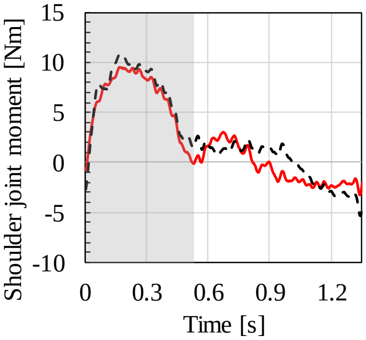


Fig.2 An example of estimated shoulder joint moment during wheelchair propulsion. Red solid line and black broken line show estimated values using inertial sensor and 3D motion measurement system, respectively. Shaded area shows propulsion phase.

Figure 5 shows the average value of each index. The plots are shown for 2 load conditions: low propulsion load and high propulsion load. The load conditions were divided by the threshold value of F_R (14 %BW) that was determined by the additional experiment of wheelchair running on flat surface and 6.0% slope described above. Although differences in the average values between load conditions were small, there were significant difference ($p<0.01$) in the change with sub 2. Caused changes were different between subjects and between indexes. Figure 6 shows change of average value of the index between low and high load conditions. Under the high load condition of subject 1, F_R/M_S decreased, F_T/F_R increased, and F_T/M_S decreased compared to low load propulsion condition. On the other hand, in subject 2, all indexes increased under the high load condition. In subject 3 all indexes were decreased under the high load condition.

IV. DISCUSSIONS

Since correlation coefficient between F_R/M_S and F_T/F_R and between F_T/M_S and F_T/F_R were low, proposed indexes are considered to have different information from the index F_T/F_R based on the previous study. Subject 1 showed decrease of F_T/M_S, which meant that contribution of shoulder joint moment to wheelchair propulsion decreased. Since F_T/F_R increased with subject 1, the deterioration of the contribution of the moment to wheelchair propulsion was considered to be caused by decrease of contribution of joint moment to the resultant force on handrim (F_R/M_S). Subject 3 also showed the

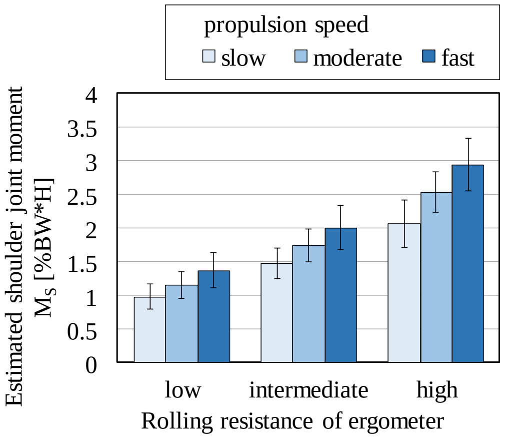


Fig.3 Peak values of estimated shoulder joint moment in a single stroke movement.

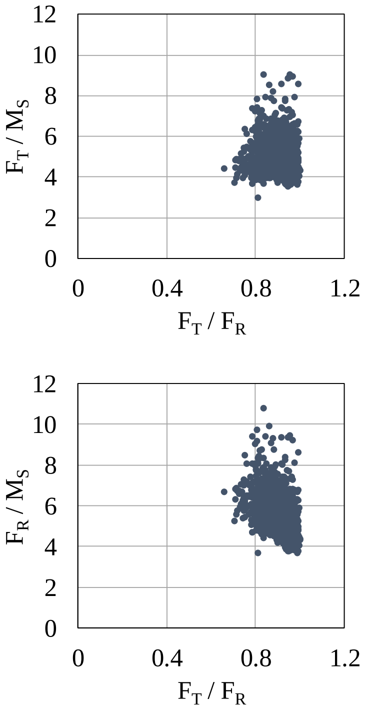
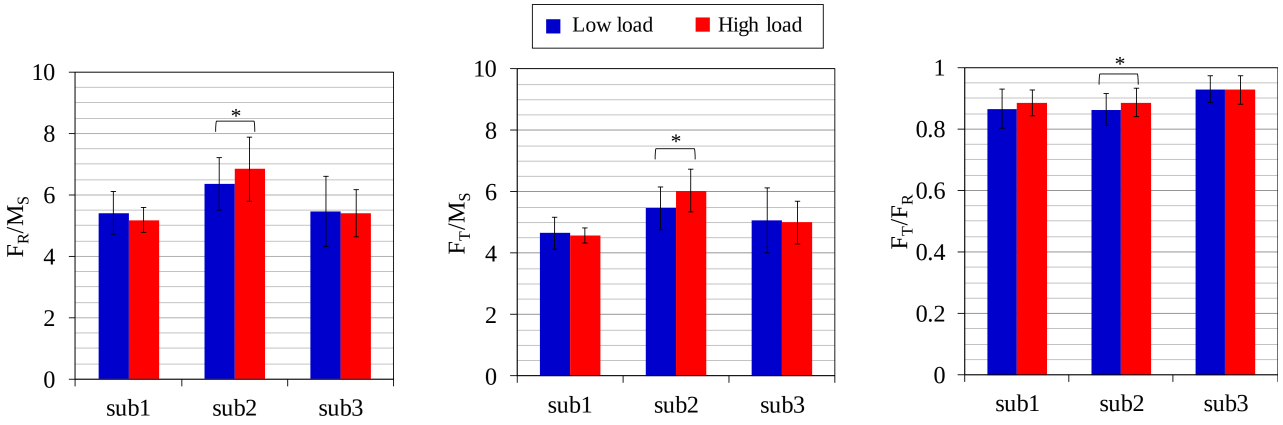


Fig.4 Relationships between the proposed indexes and the ratio F_T/F_R. Values obtained from all subjects are plotted.

TABLE 1 Correlation coefficient between indexes.

	Sub 1	Sub 2	Sub 3
F_T/M_S vs. F_T/F_R	0.09	-0.001	0.10
F_R/M_S vs. F_T/F_R	-0.51	-0.40	-0.15



(a) F_T/M_S (b) F_R/M_S (c) F_T/F_R

Fig.5 Average value of each index for low and high load condition. * shows significant difference ($p<0.01$).

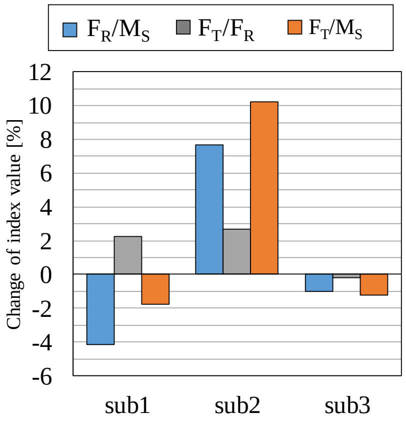


Fig.6 Change of average value of the index between low and high load conditions.

decrease of the contribution of the moment to propulsion similarly. However, both of F_R/M_S and F_T/F_R decreased with subject 3. Therefore, both of F_R/M_S and F_T/F_R might be the cause of decrease of the contribution to wheelchair propulsion. On the other hand, Subject 2 showed increases of F_R/M_S and F_T/F_R, which were considered to increase F_T/M_S. Evaluation indexes derived from joint moment is considered to make it possible to provide information of the contribution of joint moment to resultant force and to wheelchair propulsion. This suggests that using joint moment in addition to the previously used index F_T/F_R would be effective for evaluation of wheelchair propulsion. For example, both of reducing shoulder joint moment and increasing the contribution to the forces on the handrim are expected to help training to learn an upper limb movement of wheelchair propulsion for decreasing of shoulder pain.

In this paper, shoulder joint moment was estimated only in the sagittal plane. However, it might be important to estimate shoulder joint moment in another plane. Especially, force on the handrim is generated not only in sagittal plane but also in another plane if chamber angle of rear wheel of the wheelchair is not zero. In addition, the subjects in this paper were not manual wheelchair users and the number of subjects was 3. It is considered that small changes of the indexes between load conditions are because of non-wheelchair users. Large difference in values of such index have been shown between paraplegic and tetraplegic subjects [5, 6]. Further analysis in wheelchair propulsion with many wheelchair users is required. From such analysis, the meanings of the indexes and the way to use of them in evaluation of wheelchair propulsion would be made clear.

V. CONCLUSION

Whilst the manual wheelchair assists increase of independency of wheelchair users, the users are often suffered from shoulder pain since it needs repetitive movement of upper limbs to propel it. In order to evaluate effective wheelchair propulsion, two indexes derived from shoulder joint moment were examined under the change of propulsion load with able bodied subjects. Correlation coefficients between the proposed indexes derived from joint moment and the index based on applied force on handrim were low. This result suggested proposed indexes had different information from the index of effective force. The changes of the indexes between low and high load conditions were different between subjects and between indexes. This result suggested that the indexes derived from joint moment in addition to the index of effective force would be useful for evaluation of load of wheelchair users. The indexes are expected to provide information to help wheelchair propulsion in decreasing of shoulder pain. Since the subjects of this study were non-wheelchair users, further analysis with wheelchair users is needed.

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