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BIO-MECHANICS MEASUREMENT OF WHEELCHAIR PROPULSION BY A MATHEMATICAL LINK MODEL

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Abstract

It is very important for disabled persons to be able to select the adequate wheelchair based on reasonable guideline. However, the method of evaluating the fitting between user and the selected wheelchair has not been established. The mechanical work of the upper limbs and the maximum values of joint torques in wheelchair propulsion are candidates as reasonable criteria of the fitting. In this paper, a new wheelchair has been developed which equips several sensors to measure the dynamic variables on the wheelchair and the upper limbs. It is shown that the proposed criteria, the mechanical work and the maximum torques, can be calculated from the measured variables. Eight persons with spinal cord injury were involved in the experiments of wheelchair propulsion. The evaluated results have been considered in the case when the position of the wheel axis is changed in the experiments. It is verified by the experimental results that the proposed criteria are useful for fitting between users and wheelchairs.

Key words : Biomechanics, Bio-Motion, Wheelchair Propulsion, Joint Torque, Mechanical Work

Introduction

The wheelchair is a typical device to help elderly people or people with disabilities who have difficulty in walking or moving. However, the efficiency level of such movement is at most about 10%, which is much less than the 15% of arm cranking or 20% of a bicycle[1]. In addition to that, the repetitive driving action that the wheelchair user must perform every 1 second cycle or so imparts an extra physical load and fatigue, which cumulatively burden the user's upper limbs, engendering damage to a user's rotator cuff or ulnar nerve, which might then develop into a physical disorder such as carpal tunnel syndrome[2]. These problems associated with wheelchair driving can be improved, in general, based on physical characteristics of wheelchair users, to the degree to which the user tries to conform to the wheelchair[3]. However, even that possibility is not yet fully proved ; no theoretical or quantitative guidelines are available in that regard

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because such a study would require a trial and error type of testing to be repeated numerous times at one site, so that only qualitative evaluations could be discussed through an anecdotal or interview type of study.

For the present study, we concentrate on investigating the joint torque produced by the upper limbs, and quantitatively analyze the upper limb load given there when the wheelchair is driven. The joint torque is explained by the fact that the variation of muscle tension force created by the contraction and relaxation of muscle is transformed to the rotational force of the joint through the bones' link mechanism. Because the joint torque is calculable from the variations attributable to the force and the associated movements that are visible by measurement of such physical movement, it is a practical way to use to discover, quantitatively, the muscle activity of the living body, which is normally difficult to measure. For our study, we quantitatively analyzed the physical load given to the upper limbs by the wheelchair driving activity from the joint torque and mechanical work perspective. To do so, we developed a three-dimensional measuring system that facilitated measurement of the force and the moment exerted to the hand rim, along with measurement to the upper limb movement trajectory. Using that system, we measured the wheelchair driving mechanism with the cooperation of eight wheelchair users, all of whom had spinal cord damage of some kind. We analyzed the relation between the physical load to the upper limbs and the position of the driving wheel axis, which is one parameter used to determine the degree to which a wheelchair can be fitted.

Methods

Described in the following is how to calculate the joint torque of the upper limbs and the associated mechanical work for wheelchair driving.

Joint torque

The wheelchair driving movement can be recognized as a hand movement, which we understand is restricted against the hand rim. Therefore, the joint torque generated by the extraction and the relaxation of muscle can be represented by the sum of the two kinds of torque, which are the torque necessary to apply the force and the moment to the hand rim, and another that is necessary to hold or change the upper limbs' posture[4]. Based on this fact, we are going to build an upper limb model having 7 degrees of freedom (DOF) in three-dimensional space. It has 3 DOF at the shoulder joint (flexion/extension, adduction/abduction, and inner rotation/outer rotation), 1 DOF at the elbow joint (flexion/extension), and 3 DOF at the hand joint (pronation/supination, palmar flexion/dorsal flexion, and radial flexion/ulnar flexion). Then, using the reverse kinematics calculation of the Newton-Euler method, the joint torque can be calculated for each of the seven joints of upper limb, as

$$\tau = M(\theta)\ddot{\theta} + h(\theta,\ \dot{\theta}) + g(\theta) + J^T F, \qquad (1)$$

where $\tau \in R^7$ represents the upper limb joint torque, $\theta \in R^7$ is the joint angle, $M(\theta) \in R^{7\times 7}$ signifies the inertia matrix, $h(\theta,\ \dot{\theta}) \in R^7$ respectively denote the centrifugal force and Coriolis force term, $g(\theta) \in R^7$ is the gravity term, $J \in R^{6\times 7}$ is the Jacobi matrix, and $J \in R^{6\times 7}$ is the force moment exerted to the hand rim. Herein, we used the regression expression[5] of Ae *et al.* to calculate the physical associated physics parameters such as the mass, the center of gravity, and the inertia tensor of each body segment, which are all necessary for the model calculation based on the wheelchair user's body size and weight.

Mechanical work

Variation of the speed on the tension and contraction of muscle generated in a living body is transformed into the joint torque and the joint angle speed through the bones' link mechanism. For our study, we assume that the work done by the muscle in a living body is the mechanical work transformed to each joint, and define the work as follows using the product of each joint torque by each associated angle speed.

The mechanical work at each joint is given as

$$W_i=\int|\tau_i\dot{\theta}_i|\,dt, \tag{2}$$

and that of the upper limb is expressed as the following.

$$W=\sum_{i=1}^{7}W_i \tag{3}$$

Measuring System

To calculate the upper limb joint torque and the associated mechanical work, we must measure both the force and the moment exerted to the hand rim and the associated upper limb movement trajectory simultaneously. Figure 1 depicts the three-dimensional measuring system that we developed during the study.

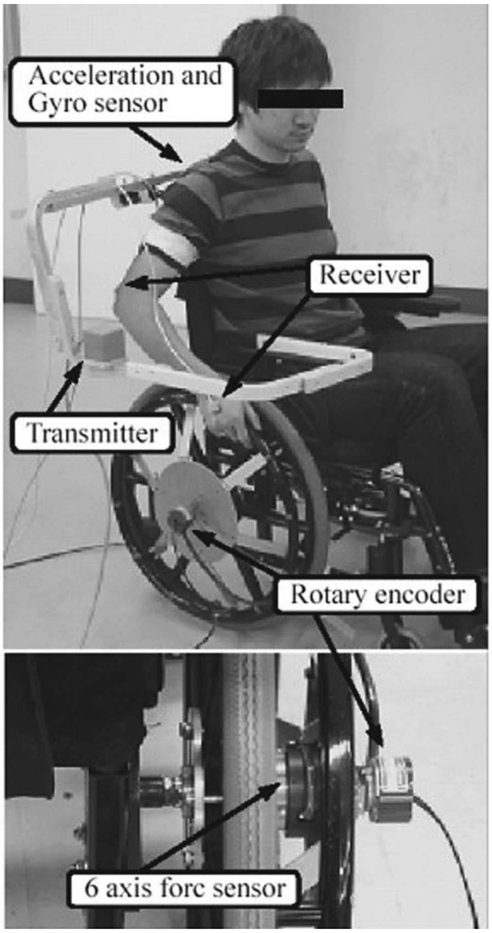


Fig. 1. Measurement system.

We used a magnetic type of three-dimensional position sensor (Fastrak; Polhemus Inc.) to measure the upper limb movement trajectory. The sensor comprises a control unit, a transmitter, and more than one receiver; it calculates the posture and the relative position of those receivers in the transmitter position-based coordinate system while detecting the variation of electromagnetic field that the transmitter generates using those receivers. For this study, we set the transmitter at the right-hand-side of a wheelchair using a wooden arm, and the receivers each at the rear side of the right forearm and at the backside of the right palm of the wheelchair user tested. Subsequently, we calculated the joint position and the associated angle of the upper limb, which has 7 degrees of freedom, using the method developed by Fujita *et al*[6]. Additionally, because the three-dimensional position sensor of the magnetic type might produce some measurement errors from some magnetic material or a metal loop around, we avoided them to the greatest extent possible by replacing the wheels and the hand rims with plastic ones. Furthermore, because the transmitter that is used as the base of the coordinate system in the measuring space is fixed to the wheelchair itself, we embedded three acceleration sensors (ADXL105AQC; Analog Devices, Inc.) and three gyro-sensors (ENC-03 J; Murata Manufacturing Co.), which were used to measure the relative movement to the inertia system.

For the three-dimensional move measurement to make on the force and the moment exerted to the hand rim, we used a special wheel for driving force measurements in which a six-axis force sensor (IFS-67M25A 50-I40; Nitta Corp.) and a rotary encoder (OIH 48-6000P4-L6-5V; Tamagawa Seiki Co. Ltd.) were embedded[4]. As a driving force measurement gauge for a wheelchair, what has been used the most from the past is a torque transducer attached on the driving wheel axis to measure the torque generated around it. However, to analyze such a physical load as produced in a living body and in the joint torque[7,8], we must measure not only the torque generated around the driving wheel axis, which contributes to the wheelchair driving directly, but also all the force and the moment that the wheelchair user applies to the hand rim. To accomplish that, we embedded a six-axis force sensor between the hand rim and the wheel, as depicted in Fig. 1. Thereby, we accomplished measurement of such force and the moment that the user applied in a three-dimensional space. In addition to that, because this measurement wheel is embedded with a rotary encoder, we can measure the rotational angle of the hand rim simultaneously.

Because such a three-dimensional measuring system as described above can be attached to the wheelchair that a user normally uses, we can obtain correct measurements reflecting each user's living situation accordingly, in addition to evaluation measurements.

Experiment conditions

We measured the wheelchair driving of a wheelchair user with the measuring system we developed, which was attached to a modular type of wheelchair (Swing ; Scandinavian Mobility International A/S) that was commercially available, and which was made with 5-inch casters, 22-inch driving wheels, 20-inch hand rims, 38-cm seat width, and 14.2 kg weight. We tested eight wheelchair users, all of whom had spinal cord damage somewhere between the thoracic segments and the lumbar segments : all were males of 55±15 years of age, with 167.5±7.5 cm height, and 63.5±11.5 kg weight. During a series of experiments, we measured the driving for the straight direction movement, with special emphasis on the driving wheel axis position, which is one parameter used to determine how the wheelchair is fitted to the user, while shifting it by 2.5 cm in either the forward or rearward direction. Each time, measurements we made were as presented in Fig. 2. Based on advice from an occupational therapist who had good on-site experience with a wheelchair fitting process, we determined and set the driving wheel axis position B, which acted as the base position for the measurement. Thereby, the position of the tested user hands came as high as the driving wheel axis position when the hands were hung straight downward. For that reason, the inward angle of the elbow was 120° when it was placed on the top of the hand rim. The driving wheel axis position A was set 2.5 cm back from B ; that of C was set 2.5 cm in front of B. The wheelchair driving speed was determined at the tested user's discretion. We then measured the driving four times each time while moving the wheelchair from its original halted position. The measurement sampling was made every 20 Hz. The experiment was performed with the informed consent of all tested users.

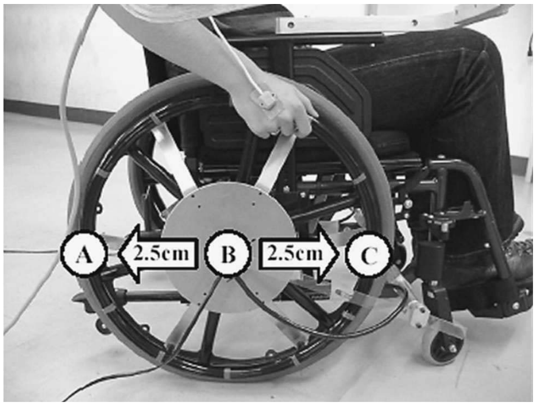
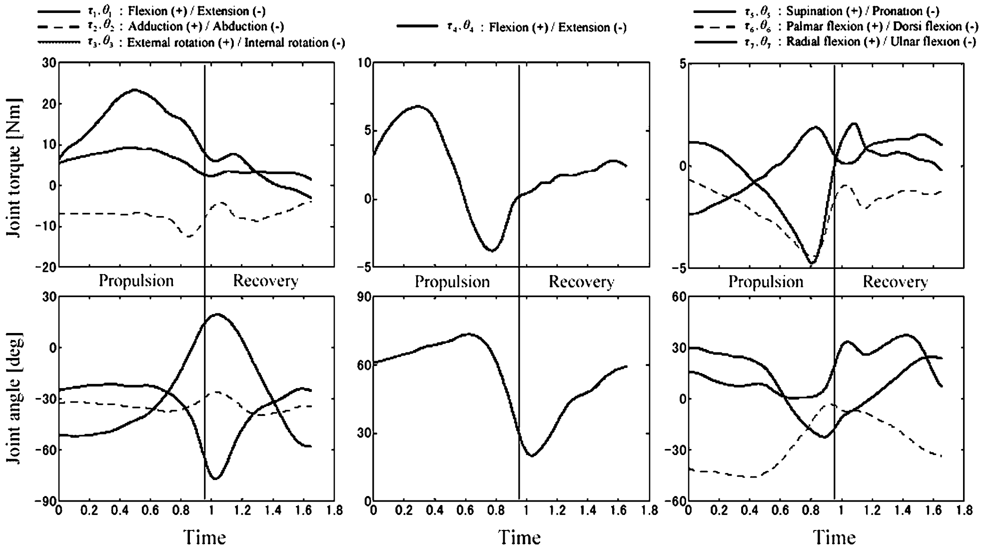


Fig. 2. Experiment conditions.

Results

In this study, we concentrated on investigating the first stroke made from the halted state, which was thought to require the greatest driving force—driving and a swing back of upper limbs—to determine the relation between the physical load imparted on the upper limbs and each associated driving wheel axis position.

Figure 3 portrays an example of variations resulting from the joint torque and the joint angle. Among them, examining each of the joint torques



(a) Shoulder joint (b) Elbow joint (c) Wrist joint

Fig. 3. Joint torque and angle of the upper linb.

obtained, it is apparent that the greater the torque in the direction of flexion, abduction, and outer rotation of the shoulder is and the further the joint is away from the elbow joint and the hand joint, the smaller that joint torque becomes. Additionally, it is apparent that the elbow joint torque has a peak in its value in the direction to which it is bent or stretched. That is because the elbow takes a series of movements to pull the hand rim toward the trunk of the body and then push it outward in the next step. The results we obtained agree with the analysis made by Sara, *et al.*[9] of the electric potential of muscles. That study showed that the muscle activities made by the flexor of the shoulder joint, and the pectoralis major muscle and the supraspinatus muscle, each of which is an abductor, are the strongest of all. The biceps brachii muscles and the triceps brachii muscles, which are, respectively, the flexor and extensor of the elbow joint, act alternately each in the first half and the last half of the driving process.

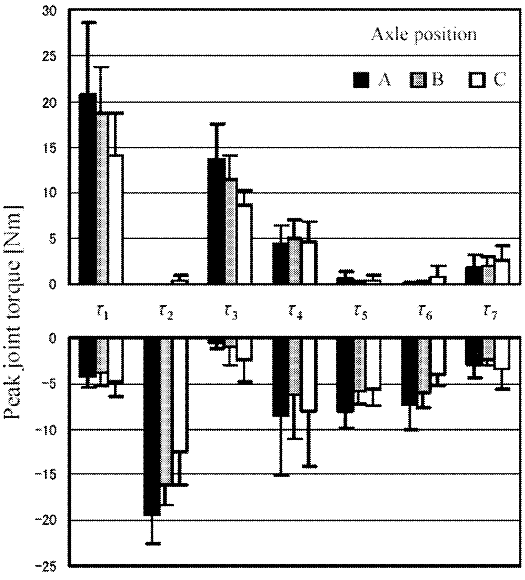


Fig. 4. Peak joint torque.

Figure 4 portrays the joint torques obtained by each of the tested users in terms of their peak value average and the associated standard deviation taken for every driving wheel axis position. The figure shows that the peak value of each joint torque increases as we move the driving wheel axis position backward from its base position B to the position A. It decreases as we move it forward from B to C. Especially at driving wheel axis position C, a significant decrease of the peak value toward the direction of each flexion is apparent, in addition to abduction and outer rotation of the shoulder joint and each pronation and dorsal flexion of the hand joint. Based on these results, we infer that we can reduce the physical load imparted on a user's upper limbs by setting the driving wheel to move and fix in a slightly more forward position.

Figure 5 depicts the average values of the mechanical work done by each joint, and their associated standard deviations. It is apparent that the mechanical work done by each joint is the largest toward the direction of flexion and extension of the shoulder joint, and that the more we move the driving wheel axis position from A to C, the more reduction is caused.

Figure 6 portrays the average values of the mechanical work done in all by upper limbs and their associated standard deviations. The mechanical work done by the upper limbs increased by 10% when we moved the driving wheel axis position backward from B to A. It decreased by 15% when we moved it forward from B to C. Applying the t-test to that mechanical work, we found a statistically significant difference for each work value ($p<0.05$). Therefore, we conclude that setting the driving wheel in a more forward position is an efficient method to reduce the physical load onto the upper limbs from the upper limbs' mechanical work perspective.

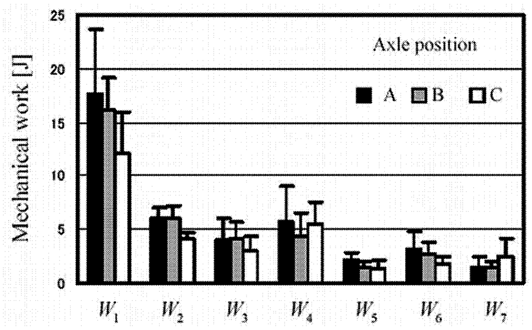


Fig. 5. Mechanical work.

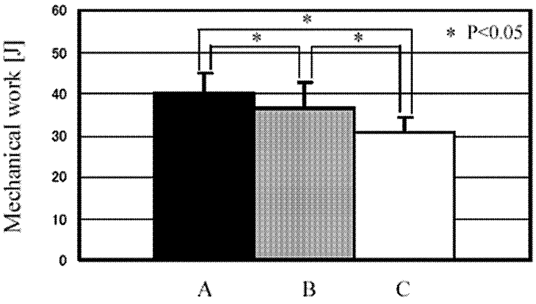


Fig. 6. Gross mechanical work.

Discussion

Based on the results we obtained, we found when we moved the driving wheel axis position of a wheelchair in the forward and backward directions along A, B, and C that the physical load imparted to the upper limbs at position C was the smallest of all. Regarding the fact that the physical load to the upper limbs varied as the driving wheel axis position shifted, we can imagine two reasons. One is that the rolling resistance varies as the driving wheel axis position shifts. The rolling resistance generated in the gap separating the wheelchair wheel and the street surface varies as the ratio of the total wheelchair load shared by the driving wheel and the casters changes. It decreases as the center of gravity of both the wheelchair and its user comes closer onto the driving wheel axis of the wheel[3,7]. Table 1 presents the ratio of the total wheelchair load when shared by the casters and the driving wheel. It tells us that the load share taken by the driving wheel increases as the driving wheel axis position is moved forward from A to C, thereby reducing the rolling resistance. The rolling resistance, whether it is small or large, causes a direct impact to the driving force for a wheelchair, which we had inferred was one reason for changing the

Table 1. Ratio of wheel load

	A	B	C
Caster [%]	27.3	26.4	21.0
Rear wheel [%]	72.7	73.6	79.0

physical load to the upper limbs. Another reason is the change of the upper limb posture caused by the driving wheel axis position difference. How easily a human being can put the user's force to the user's hand position depends upon the mechanical structure of the muscles and bones of the user. Every muscle characteristic that each user has and every upper limb posture that a user takes makes a big difference[10]. For the reasons described above, every wheelchair user has their own posture with which they drive a wheelchair easily or not easily. The result actually depends on the effectiveness of the user's posture, which varies the physical load amount to the user's upper limbs.

Conclusion

During this study, we developed a three-dimensional measuring system with which one can measure the upper limb movement trajectory and both the force and the moment exerted to the hand rim. The system can analyze, quantitatively, the physical load imparted on the upper limbs when the wheelchair is driven. Then, by calculating the mechanical work and the joint torque produced at the upper limbs of the eight people who had all experienced damage to their spinal cord, we specified the relation between the driving wheel axis position and the physical load given to the upper limbs. The results obtained from our study were that the further we move and set the driving wheel axis position toward the front side of the wheelchair, the less physical load was imparted on the upper limbs. Those results agree with what wheelchair users have reported; they also agree with the experiences that occupational therapists and physiotherapists have had. Consequently, we believe that we can add unbiased guidelines to experience-based evaluations in the relevant literature on this subject as to whether wheelchairs are well fitted to users or not. Future studies will be undertaken to determine the physical load to the upper limbs more quantitatively by examining further inside the living body using measurements of muscle tension and consumption energy. Future studies will also analyze the relation between the wheelchair shape and the wheelchair user.

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