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Evaluation of a Competition Wheelchair Based on Estimation of Muscle Activity for Forward Linear Operation by Using Inverse Dynamics Analysis †

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Abstract: The objective of this study was to evaluate an optimum structure for a rugby wheelchair by estimating the muscle force during forward linear operation of the wheelchair using an inverse dynamics analysis. The simulation model was represented by restraining the contact area between the frame and seat of the wheelchair and the body model. Three body model variations were constructed with different degrees of disability. Wheelchair models were also constructed by varying the range of camber angle, wheel diameter and axle positions, respectively. The effects of the design parameters for the wheelchair on the muscle force were investigated. As a result, the axle position had the strongest effect on the muscle force of the upper limbs, and it is effective to lower the axle position for reducing the muscle force required. This implies that the adjustment of the axle position leads to a reduction in risk of injury occurrence.

Keywords: inverse dynamics; muscles; musculoskeletal models; wheelchair rugby; disability sport

1. Introduction

In wheelchair rugby, the wheelchair is required to have operability to avoid collision, in addition to durability during impacts. Therefore, for athletes, muscle load emerges from wheelchair operation and impacts between wheelchairs. The study observed wheelchair rugby athlete's muscular strength and shoulder pain reports, which stated that shoulder pain and muscle weakness are caused by atrophy of the muscles around the shoulder blades [1]. At this stage, in wheelchair rugby wheelchairs, the safety standard is present [2]. However, the standard that attaches special importance to the physical characteristics of athletes is not present. Therefore, it is difficult to select a suitable wheelchair for individual athletes. Consequently, it is possible that athletes are not using a suitable wheelchair for their body. A suitable wheelchair is considered to be different depending on factors such as the player's height, frame, degree of disability, etc. On the other hand, specific designs of suitable wheelchairs for athletes are unclear. Other studies have reported that shoulder pain was triggered by long-term use in a standard wheelchair [3]. However, studies have reported a validation of a musculoskeletal model of wheelchair propulsion and its application to minimize shoulder joint forces [4], etc. However, these findings are not necessarily applicable to wheelchair rugby wheelchairs. In wheelchair rugby, studies have primarily reported the improvement of physical function by training in sports, such as improving pulmonary function in people with tetraplegia by wheelchair rugby training [5], and the influence of long-term wheelchair rugby training on the functional abilities in persons with tetraplegia [6]. On the other hand, few studies have focused on the physical load on athletes and the prevention of injuries. Therefore, if it is possible to evaluate a wheelchair that incorporates physical load factors such as muscle strength, athletes makes it possible to choose a suitable wheelchair. Such an approach may make it possible to reduce the risk of injury and improve performance. From the above, this study aims to evaluate a suitable structure for a rugby wheelchair by estimating the muscle force during forward linear operation of the wheelchair using a musculoskeletal simulation analysis.

Wheelchair movement in wheelchair rugby has various movements according to the situation. However, this study aims to evaluate the wheelchair by exploring the effects of the design parameters of the wheelchair. Therefore, the movement tested was only forward linear operation.

2. Method

2.1. An Overview of Musculoskeletal Simulation

In this study, Anybody Modeling System (Anybody Technology Inc., Aalborg, Denmark, hereinafter referred to as Anybody) was used for the musculoskeletal simulation. In Anybody, a musculoskeletal model is constructed by inputting body parameters, such as height and weight of a target human body. The body model, which consists of rigid segments (bones), junctions (joints) between segments, and muscle tendons composed of physiological specificity, are constructed based on human anatomy.

The analysis method of Anybody is based on inverse dynamics. The muscles of the musculoskeletal model have redundancy of joint degrees of freedom. Therefore in Anybody, the cube of (muscle force/maximum muscle force) are computed for each muscle, additionally this sum is set as an objective function. Furthermore, the muscular force of each muscle is estimated so as to minimize an objective function.

2.2. Construction of Body Model

In Anybody, muscles have three different models, from simple to physiologically most complicated. Muscle strength of the most simple muscle model does not depend on the current length of a muscle and the contraction. Of course, actual muscles do not work in that way. However, if muscle contraction rate is not fast, a simple model is sufficient for reasonable operation. In addition, muscle contraction rates in forward linear movement of a wheelchair had a moderate contraction speed in this study. Therefore, this analysis is considered to have no problem with accuracy without the use of a complicated muscle model. From the above, a body model was constructed by simplest muscle model in this study. Classes in wheelchair rugby are set at seven levels (0.5 increments) from 0.5 to 3.5 based on the degree of disability [7]. Three kinds of body models were constructed with different degrees of disability. The models are aimed at the greatest number of players, which are in class 2.0, which was set from the sum of scores based on degrees of the disability of the upper limbs and trunks.

Wheelchair rugby athlete's body models are in need of decreased muscular strength of upper limbs or trunk. Because of this, the body model of a healthy person was prepared as a control model setting base muscle strength. This body model is the standard model installed in Any Body. This model is based on the physique of westerners, with a height of 180 cm and a weight a 75 kg. Body models were constructed by setting a decreased muscular strength due to disability in this model. In the body model, muscular strength was set according to points allocated based on the upper limbs and trunk (Table 1).

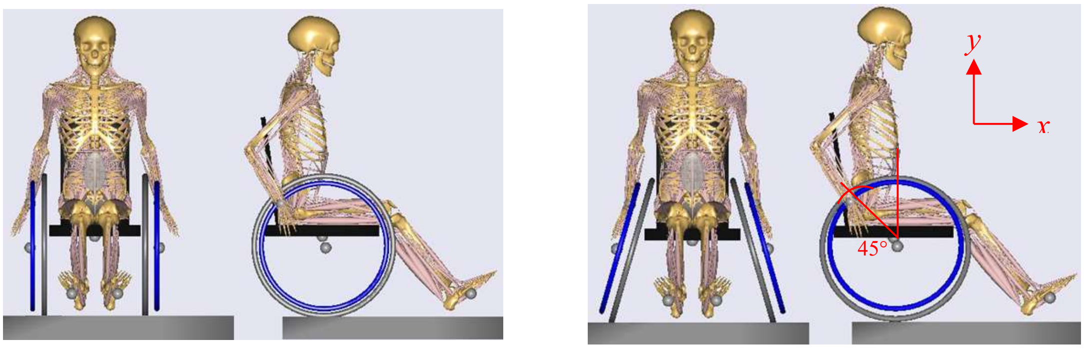
Table 1. Strength setting by muscular dysfunction.

Model	Body Model of Class 2.0 (Score of Upper Limb + Trunk)	Strength Setting (×Healthy Subject)	
		Upper Limbs	Trunk
A	0.5 + 1.5	1/5	1
B	1.0 + 1.0	3/5	5/8
C	2.0 + 0.0	1	1/8

2.3. Construction of Wheelchair Model

In order to estimate the muscle strength during forward linear operation of the wheelchair, wheelchair models were constructed. The wheelchair design parameters focused on camber angle, wheel diameter, and axle positions in this study. Moreover, muscular strength during forward linear operation of the wheelchair was investigated when changing these design parameters.

The design parameters of the wheelchair model (Figure 1a) are 609.6 mm for the wheel diameter, 7.5 kg for the mass, 232.5 mm for the distance between the axles, and the axle position is 15 mm forward and 5 mm below the center of the seat. Based on the model in Figure 1, wheelchair models were constructed by varying the range of camber angle (4-grade, 2° intervals), wheel diameter (3-grade, 25 mm intervals) and axle positions (5-grade, 50 mm intervals up/down and fore/rear) (Table 2). The other design parameters are the same as those of the model (Figure 1). The structure omitted components that are unique to wheelchair rugby wheelchairs, such as bumpers, because this examination was conducted without considering influences at the time of collision.



(**a**) (**b**)

Figure 1. Referred wheelchair model for constructing wheelchair rugby model (**a**); and constructing wheelchair rugby wheelchair model (**b**).

Table 2. Setting of each parameter in competition wheelchairs.

Camber Angle (°)	Wheel Diameter (mm)	Axle Position (mm)	
16 18 20 22	609.6 635.0 660.4	Center: Forward: Rear: High: Low:	Standard Position (SP) SP + 50 mm, *x* SP − 50 mm, *x* SP + 50 mm, *y* SP − 50 mm, *y*

2.4. Expression of Wheelchair Forward Linear Operation

A simulation model was constructed where a body model was seated on the constructed wheelchair model. Between the body model and the wheelchair model there were restraints connecting the pelvis and seat, as well as the foot sole and footrest. The vertical direction from the axle is defined as 0°, and the initial position of a wheelchair rugby wheelchair is set at −45° (Figure 1b). For the simulation model, straight-ahead operation was expressed by giving the axle an angular velocity of 1.57 rad/s. The analysis time was 1 s from the start of operation.

3. Result

3.1. Analytical Results

Results from our inverse dynamics analysis match trends with the muscle activity during forward linear operation for wheelchairs measured by electromyogram [8]. Although there is no concordance of results because it is not patient-specific modeling, this parallel in trends has certain reliability in the result of modeling output in this study.

3.2. Estimation Results

For the constructed simulation model, the muscle force was estimated by inverse dynamics analysis. In the analysis, the muscular strength of the upper limbs was estimated, and muscle strength was investigated an influence on the wheelchair design parameters. The trunk muscles were omitted this time because the overall trend was not observed depending on conditions.

In order to select the muscle to be investigated, analysis was performed with three kinds of body models for the wheelchair model (camber angle 18°, wheel diameter 635.0 mm, center of axle position) (Figure 2). From this result, the muscles to be investigated were triceps brachii and subscapularis which exhibited robust muscle strength in all models. The muscle force of the triceps brachii increased as the motion progressed in both model A and B, and peaks were seen 0.989 s from the commencement of the operation. On the other hand, in model C, the peak was shown around 0.25 s following the commencement of the operation. In addition, the muscular strength subsequently decreased. It follows from the result that a body trunk works for postural maintenance in healthy persons, by contrast, the muscular strength of the trunk is declining in model C. Therefore, it is estimated that triceps brachii works for postural maintenance instead of the body trunk.

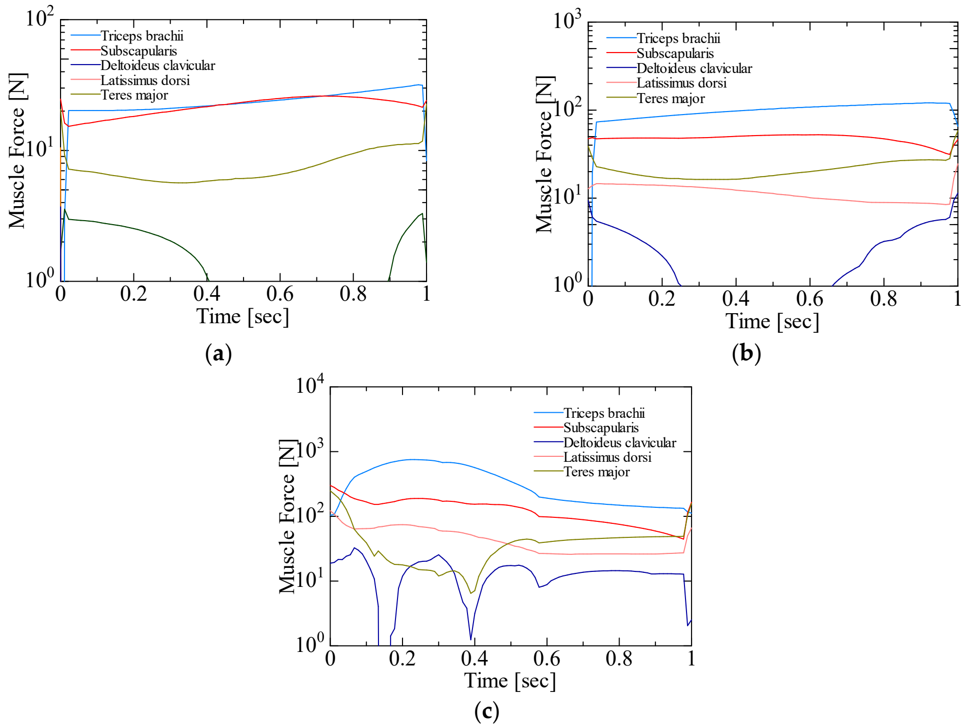


Figure 2. Muscle strength histories in upper arm, (**a**) model A; (**b**) model B; (**c**) model C.

For the subscapularis muscle, models A and B showed a peak around 0.7 s after the commencement of the operation. Model A exhibited muscle force almost equal to the triceps brachial at the peak time, whereas in model B there was a large disparity in muscle force. Because of this, it is assumed that the subscapularis muscle has no role in maintaining posture; it is only working on the propulsion action.

4. Discussion

4.1. Comparison of Estimated Muscle Force

The muscle exercise data estimated by the inverse dynamics analysis were compared for each condition of the wheelchair model. It appeared that the camber angle has no effect on muscle force. Therefore, the camber angle was fixed at 18°, the analysis results with other design parameters changes were compared (Figures 3 and 4).

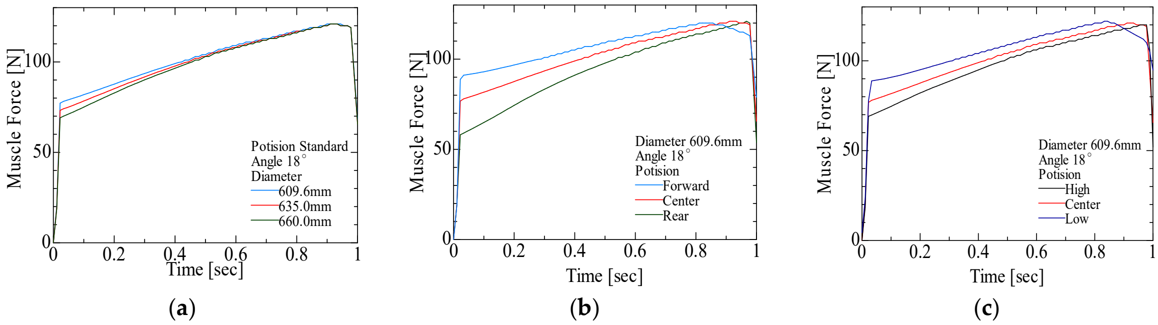


Figure 3. Comparison of muscle strength in the triceps brachialis muscle (model B). (**a**) Wheel diameter; (**b**) Axle position (Forward ~ Rear); (**c**) Axle Position (High ~ Low).

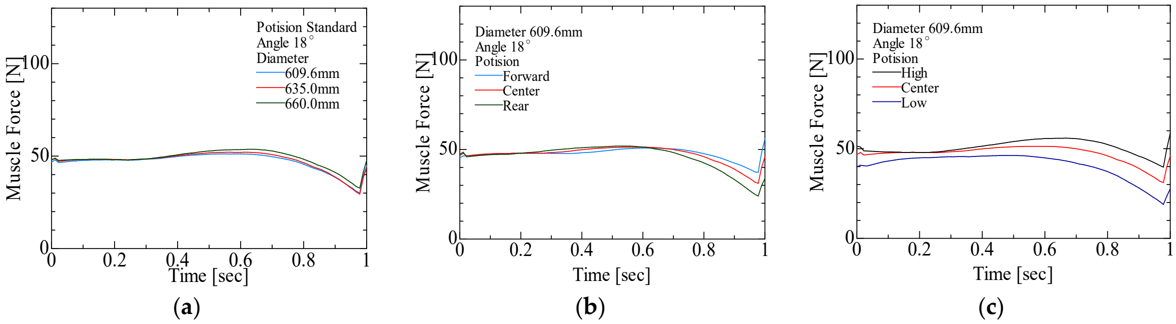


Figure 4. Comparison of muscle strength in the subscapularis muscle (model B). (**a**) Wheel diameter; (**b**) Axle position (Forward ~ Rear); (**c**) Axle Position (High ~ Low).

As a result, it was observed that the lower the axle position, the greater the muscle force of the triceps brachii. In contrast, the subscapularis tended to decrease. Wheel diameter seems to have a slight effect on muscle force. In particular, triceps brachii muscle force increased in inverse proportion to wheel diameter. However, there seems to be no effect on the subscapularis muscle. These trends differ in Magnitude of effect depending on the body model, however, in the targeted upper limbs, similar trends were found in all body models.

4.2. Evaluation of Thewheelchair

As a result of comparing the muscle strength of the upper limbs by inverse dynamics analysis, it was confirmed that the triceps brachii and subscapularis muscles did the majority of the work in the wheelchair operation. In addition, it was suggested that the triceps brachii may not only move straight ahead, but also has a role in postural maintenance of the upper body in the wheelchair forward linear operation. The subscapularis muscle is an important muscle for the stability of the shoulder joint. In addition, reports of the load on the subscapularis muscle are related to causes of injury in athletes [1]. It is suggested that if it becomes possible to reduce the muscle load on the subscapularis by adjusting the wheelchair design parameters, risk of injuries can be reduced. Additionally performance can be improved during competition. It becomes possible to evaluate that a wheelchair with such a design is an excellent wheelchair with the possibility of prevention of further disability. Based on the above findings, it was shown that an appropriate wheelchair in this study is one where the axle position is located below the standard position.

5. Conclusions

In this study, in order to conduct an analysis based on musculoskeletal simulation, body models and the wheelchair rugby wheelchair models were constructed. In addition, we estimated the muscle force during forward linear operation using the constructed wheelchair model. Moreover, the muscle force data obtained by the analysis were compared for each version of the model, and the wheelchair rugby wheelchair was evaluated based on the obtained results. As a result, the following was found:

- In the muscles of the upper limbs, the triceps brachii works for propulsion and postural maintenance, however subscapularis works only for propulsion.
- The axle position has the strongest effect on the muscle force of the upper limbs.
- Lowering the axle position is effective in reducing the burden on the muscle responsible for injury.

In conclusion, the present study has demonstrated that it is possible to evaluate an optimum structure for a rugby wheelchair by estimating the muscle force during the forward linear operation of the wheelchair using an inverse dynamics analysis. It is suggested that the design and selection of wheelchairs which would reduce the risk of injury to players, in addition to an improvement of performance could be expected.

Conflicts of Interest: The authors declare no conflict of interest.

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