ANALYSIS OF DRIVING FORCE IN WHEELCHAIR PROPULSION USING THE DRIVING FORCE CONTRIBUTION FIGURE

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Abstract
We propose the concept of the driving force contribution figure (DFCF) to clarify how efficient the user accomplishes the wheelchair propulsion. The DFCF expresses the direction cosine of generated force on the handrim to the tangential direction. If the DFCF takes large value along the driving force direction, it means the applied force acts efficiently for wheelchair propulsion. In order to show the effectiveness of DFCF, we measured the driving motion of the upper limb, hand force applied to the handrim, and the individual's muscular power characteristics for eight experienced wheelchair users. From the experimental data, it is shown that the users start driving the handrim at such posture where it is difficult to generate required hand force to drive the wheelchair. It is also shown that the users are driving the wheelchair taking the load of the upper limb and the efficiency of the wheelchair propulsion into consideration.

Key words : Wheelchair, Manipulability Analysis, Driving Force Contribution Figure

Introduction

The wheelchair is an important device used for welfare and for motion by operating its hand rims with the hands, each of which must grasp the respective driving wheels. However, we can say that this mode of moving is merely a replacement of the moving functionality of the lower limbs using the upper limbs instead. Moreover, it requires force applied to the hand rims by hands repeatedly and continuously, although we understand that it does certainly give the capability of movement. Consequently, however, that unavoidable posture and motion necessary for movement using a wheelchair imposes many serious problems for wheelchair users such as the physical load that increasingly burdens the user's body, with pain resulting from accumulation of fatigue and physical disorders that might develop[1-4)].

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Recently, in attempts to solve the problems described above, the wheelchair was improved mechanically, for example, being made lightweight using carbon and aluminum alloys, or with attached shock absorbers for protection from shocks that occur during movement[5]. Furthermore, regarding how a wheelchair must be changed to fit, which has heretofore been studied through trial and error, a new mode of implementation was proposed recently with evaluations made from living body mechanics perspective in terms of, for example, the upper limb joint torque, the mechanical work to be done, and the muscle tension force[6,7]. These studies and developments are extremely important to help reduce the resistance that occurs during wheelchair driving and the physical load burdening the wheelchair user's body.

On the other hand, in light of the fact that over 50% of wheelchair users feel pain in their upper limbs and are experiencing secondarily caused physical disorders[1-4], it is reasonable to infer that a problem exists not only in the mechanical characteristics of wheelchair or how they are fitted. The actual tasks necessary to drive the wheelchair itself might be the most important causes of the increasing physical load imparted on their upper limbs. It is true that we must confront limits to improving the current situation by assessing and then perhaps altering mechanical characteristics or the process of wheelchair fitting to the user. We infer that there is a need to review the basic structure of wheelchair driving first and then augment or correct it. However, the studies that have so far been made have emphasized practical level solutions only such as how to improve the mechanical characteristics of wheelchairs based on their existing structure, or, for example, how to make them conform to users within a limited scope of adjustment. Apparently, no discussions have addressed changing the wheelchair structure itself.

With these facts in mind, in our study, we analyzed the operability of wheelchairs using Dynamic Manipulating Force Ellipsoid, and Driving Force Contribution Figure to visualize clearly how such a task as wheelchair driving conforms to upper limb movement characteristics of humans, and how wheelchair users carry out such a task.

Methods

Dynamic Manipulating Force Ellipsoid[8]

The Dynamic Manipulating Force Ellipsoid is a concept of manipulability[9] that is used to analyze the robot manipulator mechanisms. Further consideration is taken in terms of the non-symmetric maximum torque (muscle force characteristic) operable in each rotational movement direction of the seven joints of upper limbs (including a pair of flexion and extension, adduction and abduction, and inner rotation and outer rotation of shoulder, flexion and extension of the elbow, and pronation and supination, palmar flexion and dorsal flexion, and radial flexion and ulnar flexion of the hands) and in terms of the impact given to the upper limbs by the kinematics elements. Using that ellipsoid with its

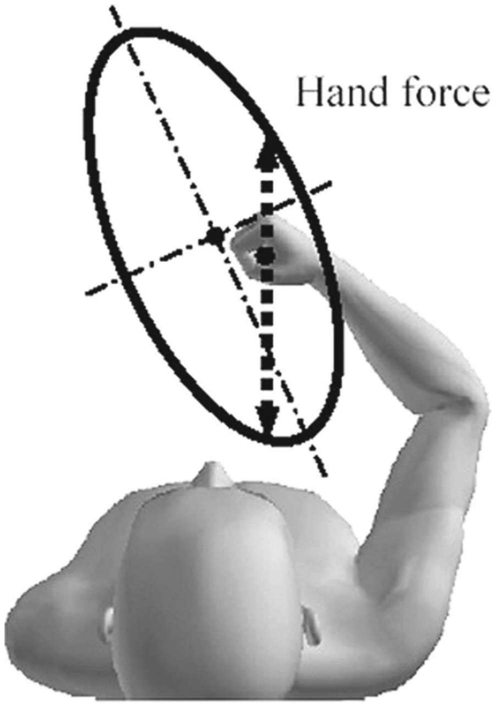

Fig. 1. Dynamic manipulating force ellipsoid.

concept, the characteristic of the force and the moment applied to the hand position can be expressed both visually and quantitatively.

Figure 1 portrays a dynamic manipulating force ellipsoid, which shows that the longer the distance is from the hand position to the ellipsoid surface, the larger the force the hand can produce ; conversely, the shorter it is, the smaller force it can produce. Moreover, the fact is shown that the center position of the ellipsoid does not coincide with the hand position, which means that the force magnitude produced in the direction in which the hand pushes and in another direction in which the hand pulls is different. In all, by measuring the maximum joint torque of the seven joints of upper limb in advance, we can analyze wheelchair operability from the upper-limb-movement characteristic perspective in terms of how each person's hand can operate it easily.

Driving Force Contribution Figure

The Driving Force Contribution Figure is a representation of the dynamic manipulating force ellipsoid with an added driving efficiency factor. It can visually express the direction in which a hand can easily impart its force to the hand rim of wheelchair to yield more driving power. For example, force F of the hand applicable to the hand rim at the hand

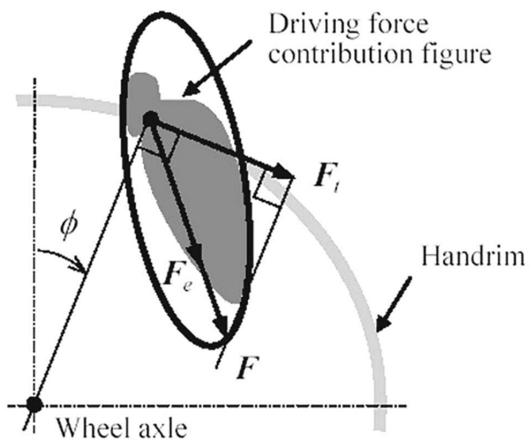

Fig. 2. Definition of driving force contribution figure.

position in all directions can be expressed using dynamic manipulating force ellipsoids, as presented in Fig. 2 (sagittal plain). Among them, when arbitrary hand force F is applied, the component F_t of the force that directly contributes to driving a wheelchair can be given by an inner product of the hand force F by the unit vector along the tangential line direction of the hand rim. We define a new vector F_e having the same direction as of the hand force F, and which has equal size to that of the hand rim tangential line direction component F_t. Then we depict each F_e for the all-direction-oriented hand force F that constitutes a dynamic manipulating force ellipsoid. Thereby, we can obtain a driving force contribution figure resembling that shown by the shaded area of Fig. 2. The figure drawn there expresses the magnitude of the force that contributes to driving the wheelchair rolling among all hand forces directed from the hand position that is placed on the hand rim. In other words, the length of the vector drawn from the hand position on the hand rim to the point on the boundary of that figure shows the size of contribution to the wheelchair driving when the hand force is applied toward such the vector direction. Therefore, we understand that the larger such a force value is in one specific direction, the more we can say that it is the direction in which the hand force can contribute most to driving the wheelchair.

Subject

To analyze the operability of a wheelchair from the upper limb movement characteristic perspective, we measured the maximum upper limb joint torque and the associated wheelchair driving capability for each joint movement of 7 degrees of freedom, which in turn was necessary to calculate the dynamic manipulating force ellipsoid and the driving force contribution figure. All eight wheelchair users we tested had spinal cord damage somewhere between the thoracic segments and lumbar segments. They were all males of 55±15 years of age, with 167.5±7.5 cm height and 63.5±11.5 kg weight. Incidentally, the experiment we made for measurements was performed based on the informed consent of all tested users.

Measurement of maximum joint torque

We used an isometric muscle strength evaluation device of Cybex (Cybex NORM ; Cybex Inc.), as depicted in Fig. 3, to measure the maximum torque of the upper limb having 7 degrees of freedom. Cybex equipment can measure the maximum joint torque continuously at every joint angle in both positive and negative directions.

For our experiment, we measured the maximum joint torque produced by the concentric contraction for every pair of movement directions : flexion and extension, adduction and abduction, and inner rotation and outer rotation at the shoulder ; flexion and extension at the elbow ; and pronation and supination, palmar flexion and dorsal flexion, and radial flexion and ulnar flexion at the hand. We repeated the experiment five times for examination of the muscle fatigue level of each tested user and at the reproduction capability of every measurement value while we set the wheel movement speed at 30 deg/s, taking the upper limb movement on wheelchair driving into consideration.

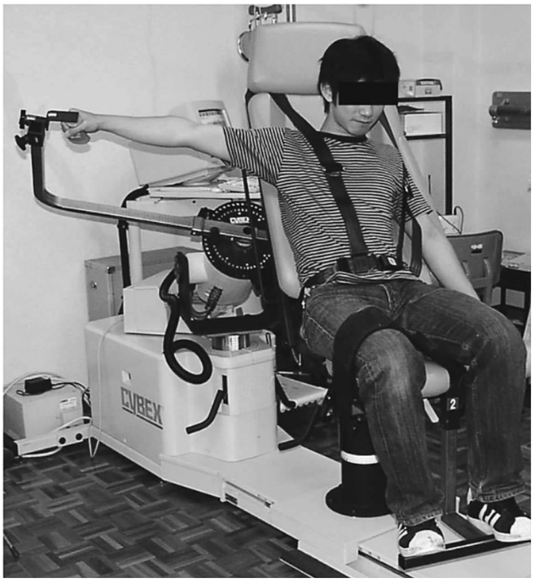

Fig. 3. Measurement of maximum joint torque.

Measurement of wheelchair driving

In Fig. 4, we depict the wheelchair driving measurement system that we developed[6]. That measuring system comprises the following : a three-dimensional position sensor of magnetic type (Fastrak ; Polhemus Inc.) for measurement of position and angle of the upper limb joint having 7 degrees of freedom ; a six-axis force sensor (IFS-67M25A 50-I40 ; Nitta Corp.) for measurement of force and the moment exerted to the hand rim ; a

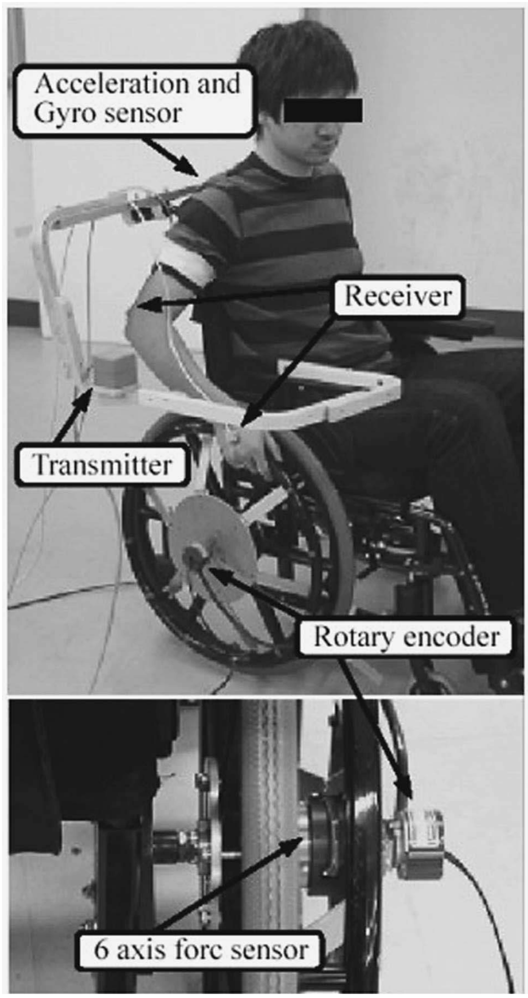

Fig. 4. Measurement system.

rotary encoder (OIH 48-6000P4-L6-5V ; Tamagawa Seiki Co. Ltd.) for measurement of the rotational angle of the driving wheel ; an acceleration sensor (ADXL105AQC ; Analog Devices, Inc.) for measurement of wheelchair acceleration and angle acceleration ; and a gyro sensor (ENC-03J ; Murata Manufacturing Co. Ltd.).

During our experiment, we measured the movement of the modular type of wheelchair (Swing ; Scandinavian Mobility International A/S) with 5-inch front wheels, 22-inch driving wheels, 20-inch hand rims, 38-cm seat width, and 14.2 kg weight, letting it drive at its free running speed on the flat floor indoors with the attached measuring system we developed. Based on advice from an occupational therapist who had good on-site experience with wheelchair fitting processes, we adjusted and set various places of the wheelchair. The position of the tested user hand came as high as the driving wheel axis position when the hand was hung straight downward; the inward angle of the elbow had 120° was when it was placed at the top of the handrim.

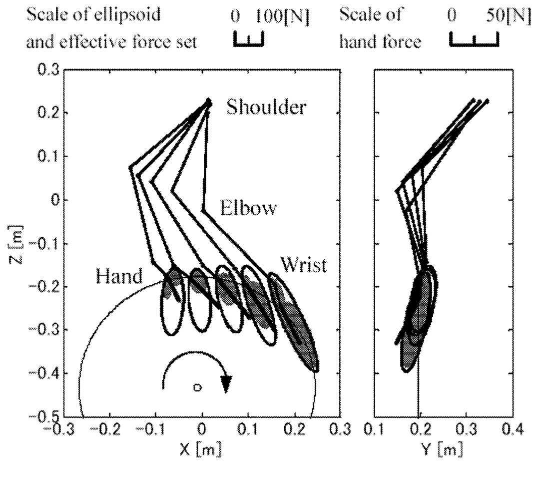

Fig. 5. Stick figure of the arm, hand force, ellipsoid and driving force contribution figure.

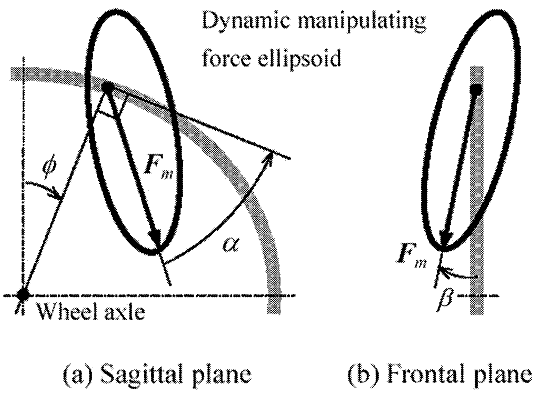

Fig. 6. Angle of dynamic manipulating force ellipsoid.

Results and Considerations

Figure 5 depicts the upper limb posture taken at the first stroke given from the halt state, the measurement results of the force vectors applied to the hand rim, and the calculation results of each upper limb posture in the form of dynamic manipulating force ellipsoid and driving force contribution figure in terms of the stick line diagram on the (a) sagittal plain and (b) frontal plain. That stream of processes is shown in a continuous fashion. Looking at it, it is apparent that what is necessary to drive a wheelchair efficiently is to increase the hand force component toward the hand rim tangential line direction because the hand rim, which is the operable part of wheelchair, has only one degree of freedom, which is the rotation around the driving wheel axis. Based on that fact, we looked at the direction to which the hand force could be imparted easily as expressed by the ellipsoid of Fig. 6, and the direction to the hand rim tangential line ; then we analyzed the wheelchair operability.

Figure 7 portrays the average value and the associated standard deviation for the eight tested users related to the maximum hand force F_m and the angles α and β taken toward the hand rim tangential line direction. The figure shows that the direction to which the hand force can be applied easily is coming to shift gradually as the wheelchair proceeds from the hand rim tangential line direction

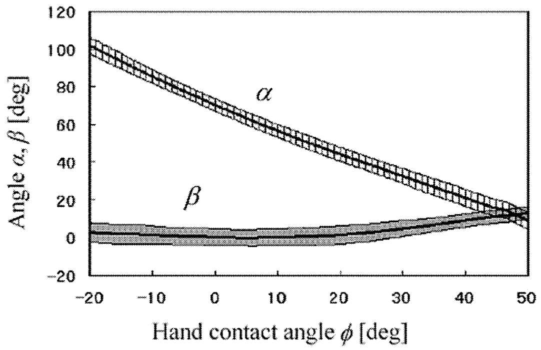

Fig. 7. Angle of dynamic manipulating force ellipsoid.

in the sense that the angle α of the sagittal plain is getting smaller. This represents that the large hand force is applied to the hand rim efficiently in the last half of the driving process. On the other hand, during the first half of the driving process, angle α differs by over 50°, in which case the hand force, if it were applied to the direction to which the hand force can be easily given, would not be transmitted properly toward the hand rim tangential line direction. Even if it were applied to the hand rim tangential line direction in a straightforward way, the fact is that the direction would be to where the hand force is difficult to apply, causing an increase in the physical load given to the upper limb of the wheelchair user. Furthermore, when the wheelchair starts to move, the angle α difference is greater than 90°, in which case the hand force is easier to apply to the direction to move the wheelchair backward than forward. We understand from that fact that wheelchair driving must be started when the upper limb posture is not yet in a good operable state : that certainly increases the physical load imparted on to the upper limbs of a wheelchair user. Next, looking at angle β to the frontal plain, it is readily apparent that the direction to which the hand force can be imparted easily differs from that of the hand rim by an angle of 5–10°, which tells us that attaching the hand rim and making it shift slightly toward the outside would be an improvement. In other words, a camber angle for the driving wheel is a good way to transmit hand force efficiently. In the past, the camber angle was said to be efficient for use in producing stable wheelchair driving on the road with a ramp existed in a sideward way and for prevention of interference between the upper limbs and the hand rims[5]. Furthermore, we think that it is worth having from a quantitative analysis perspective and from the user's upper-limb-movement characteristic perspective.

Next, we examined the direction to which the hand force was easily given, as expressed by the ellipsoid, together with the direction in which it was actually applied to the hand rim. Previous studies by ourselves and others with testing conducted with people who had no disabilities tell that such both directions as described above mostly coincide in both the first half and the last half of the driving process. However, from the experiment we made with actual wheelchair users, we were unable to obtain the same results as those presented in Fig. 5 because, as clearly depicted in the results in Fig. 7, applying the hand force to the direction in which it is easily given does not necessarily engender efficient driving power production. In addition to that, another reason might be that the long-term wheelchair user knows and is performing an efficient mode of driving (having skill differences) in one way or another with as much physical load as it is possible to give. Knowing these facts, we further examined the results we obtained using the driving force contribution figure, and clarified the definition of the hand force pattern for wheelchair driving.

Figure 9 shows the average value and the associated standard deviation for eight tested people with respect to the maximum hand force F_{em} and the angles α' and β' that the hand force F produces, which are all shown with the driving force contribution figure defined in Fig. 8. For that reason, except for the time the wheelchair starts to move, those average values agree with the fact that the angle α' on the sagittal plain is about 10° and that angle β' on the frontal plain is 20°, which tells us that the user is applying the hand force to the right

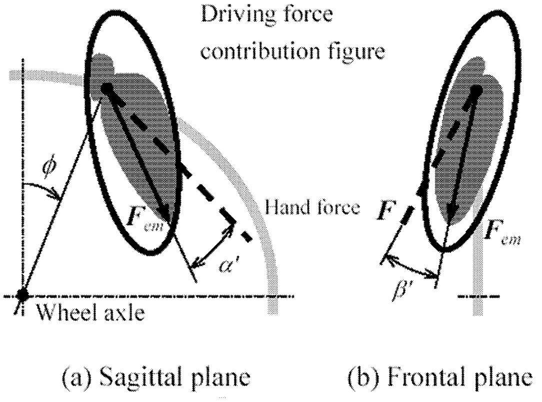

Fig. 8. Angle of dynamic manipulating force ellipsoid.

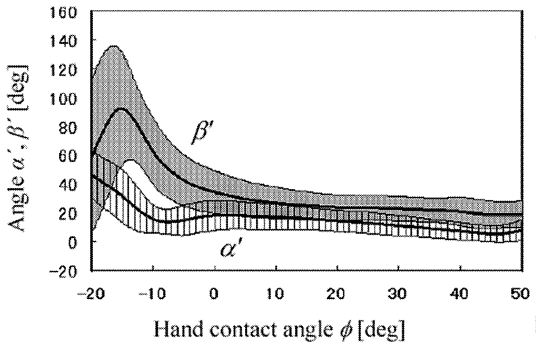

Fig. 9. Angle between driving force contribution figure and hand force.

with as much driving power as can be produced. The reason for such a difference of hand force direction occurs at the time a wheelchair starts to move is that the wheelchair user presses the hand rim in the perpendicular direction to the hand rim to produce the friction force between the hand and the hand rim. That is certainly a necessary task to start driving the wheelchair from its initial halted state. Most wheelchair users do not seem to hold the hand rims, but rather just press them using their palms to drive. That tells us that the hand force applied to the perpendicular direction to the hand rim is also necessary to transmit the hand force to the tangential line direction to the hand rim, although it does not contribute directly to driving. Especially at the time a wheelchair is moved from its halted state, it requires a large initial driving power. That is thought to be the reason for the difference of hand force direction, as shown in Fig. 9. Taken together, these results reflect that the wheelchair user is taking consideration of both efficiency and physical load given to his or her upper limbs, and is performing a very skillful operation for the task that he or she is given for wheelchair driving. That is confirmed to be true because, except for the time a wheelchair must be moved initially, the direction to which the hand force was actually applied agrees mostly with the direction to which the driving force is producible more and more easily.

Summary

For this study, we analyzed wheelchair operability using the driving force contribution figure and the dynamic manipulation force ellipsoid based on each user's muscle strength measurements. In doing so, we sought to clarify our perspective of the task of wheelchair driving from the aspect of upper limb movement characteristics, and to clarify how the user would carry out such a task. The results we obtained are as follows.

(1) During the first half of the process of driving a wheelchair, it is apparent that the direction to which the hand force is easily applied—because it is expressed using a dynamic manipulating force ellipsoid—differs greatly from the hand rim tangential line direction. Therefore, the wheelchair must be started with the upper limb posture with which it is difficult to operate.

(2) During the last half of the wheelchair driving process, the direction to which the hand force is easily applied agrees with the hand rim tangential line direction, so that an efficient driving force can be produced.

(3) Given a camber angle to the driving wheels, the hand force can be transmitted efficiently to the hand rim.

(4) The direction in which the driving force can be easily produced, as expressed in the driving force

contribution figure, agrees mostly with the hand force direction applied to the hand rim. Therefore, we infer that the user is performing the given task in an efficient way while taking the balance between the load imparted on the upper limbs and efficient wheelchair operation both well into consideration.

As described above, the study we made was to analyze the wheelchair operability quantitatively for the first time from the upper limb movement characteristic perspective in terms of how each was able use hand force efficiently. Through this study, it is apparent that not only can we express the upper limb movement characteristic of each quantitatively, but also that the study is useful to predict the hand force pattern taken for the given task that the user must perform. Therefore, combining that fact with the optimized calculations[10,11] we have proposed, we believe we can reasonably design the position and the diameter size of a hand rim with which every individual user can perform the best-fit task with a wheelchair. We can also develop a new wheelchair structure, for example, using a simulation method. Even for design of a power-assist type of wheelchair, future studies might provide good basic knowledge based on each user's upper-limb-movement characteristics with respect to what level of wheelchair strength and what timing we can use to assist the user to eliminate pain and to protect them from physical disorders that might develop.

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