Driving Tests and Computer Simulations of Electric Wheelchairs on Snow-Covered Roads*

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Not only handicapped people but also elderly people living in Hokkaido, the northernmost island in Japan, desire to participate in outdoor activities during a winter season that is characterized by heavy snow and low temperatures. Most of these people venture outdoors to go shopping or to hospitals, even under severe conditions. A wheelchair is generally used for outdoor transport. There are, however, many problems with using a wheelchair during the winter; roads covered with snow and ice are very slippery, casters are easily buried in snow, and handrims are too cold to handle. Therefore, an appropriate wheelchair for outdoor use during the winter season is greatly desired. We are developing an electric wheelchair effective for outdoor use during the winter. In this work, three types of electric wheelchairs with front-wheel drive, rear-wheel drive and front free casters, and rear-wheel drive and mechanically controlled casters, were tested for drivability on icy roads, snow-covered roads, and indoor floors. In addition, computational methods were proposed to simulate the drivability of electric wheelchairs under snowy conditions.

Key Words: Rehabilitation Engineering, Human Interface, Electric Wheelchair, Dynamics of Machinery, Computer Simulation, Winter Road

1. Introduction

A wheelchair is the most popular device to support outdoor activities of handicapped or elderly people. Their chances to go out gradually increase with improving their QOL (Quality Of Life) because of the advances in rehabilitation technologies and welfare policies. In snowy areas, however, going out involves many difficulties and risks for them during the winter season because of roads covered with snow and ice. In particular, the Hokkaido area is covered with snow for four months from December to March.

We investigated a wheelchair to support outdoor activities during the winter⁽¹⁾. Previously, we conducted a survey of attitudes on winter outdoor activities of

247 spinal injured patients who use wheelchairs daily and live in Hokkaido⁽²⁾. From this result, we recognized that they have an active outdoor life during the winter. In spite of the severe environment in the winter, over 60 percent of patients go out often. On the other hand, the major reason they do not go out was that they have no appropriate device for transportation. The frequency of going outdoors was more than two days in a week to go shopping and to hospitals. The methods of transportation were almost always cars. However, some of them go out with the usual manual or electric wheelchair. Judging from this survey, an appropriate wheelchair to use outdoors in the winter is desired. The following basic requirements must be satisfied by a wheelchair for winter use: (1) to drive without slipping, (2) to be suitable for use both indoors and outdoors and to transfer easily between indoors and outdoors, (3) to have adequate equipment against the cold, and (4) to have a comfortable seat considering the effects of exposure to cold on the materials. Therefore, we developed a wheelchair for winter use to meet these requirements. As the first step of the project, we transformed an electric wheelchair with rear-wheel drive to one with

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front-wheel drive.

In this report, three types of electric wheelchair are described: one with rear-wheel drive and front free casters, one with rear-wheel drive and mechanically controlled front casters, and one with front-wheel drive and rear casters. These were tested for drivability on icy roads, snow-covered roads and indoor floors. The drivability of an electric wheelchair is greatly influenced by the structure and the center of gravity including a human body. It is very important to design a wheelchair appropriately by taking the individual ability of a driver and the size of the human body into account. Therefore, a computational method was proposed to simulate the drivability of each electric wheelchair. The drivability under various road conditions was then evaluated by this simulation.

2. Electric Wheelchair with Front-Wheel Drive

The typical electric wheelchair has rear-wheel drive with small casters at the front and driving wheels at the rear. The two driving wheels are each driven by independent motors and steer simultaneously. Previously, a driving test for wheelchairs on a snowy road had been carried out by Nishimura et al. at the Hokkaido Evaluation Center for the Mentally and Physically Handicapped. Although the detailed results have not yet been published, their short report can be summarized as follows:

(1) Driving a manual wheelchair in snow makes even a healthy person tired because of the resistance of the snow. If half a caster wheel is buried in snow, the wheelchair cannot move.

(2) If a small ski is attached at the caster wheels of a manual wheelchair, the chair can move to some extent. However, mounting and detaching the ski are very troublesome for a handicapped person, and the ski often comes off during driving.

Fig. 1 Electric wheelchair with front-wheel drive

(3) The drivability of an electric wheelchair depends mostly on the ability the front caster wheels to rotate.

From this report and the attitude survey, the wheelchair to use during the winter was judged to be an electric wheelchair with front-wheel drive. Therefore, as the first step in this work, a wheelchair with rear-wheel drive (MC-13P, Suzuki Co. Ltd., Japan) was remodeled to have front-wheel drive. Figure 1 shows a wheelchair with front-wheel drive made for this experiment. The net weight is 81 kg, and the supporting load rate of the front wheel is about 60 percent of the total weight of the wheelchair and the occupant. The ability of this wheelchair to be driven on a normal road entirely satisfies JIS No. T9203 (Japanese Industrial Standard).

3. The Driving Test

Three types of electric wheelchair; the FC type (rear-wheel drive and front free casters, MC13S, Suzuki Co. Ltd., Japan), the FR type (rear-wheel drive and front mechanically controlled casters, MC13P, Suzuki Co. Ltd., Japan), and the FF type (front-wheel drive and rear mechanically controlled casters), were tested for their ability to be driven on icy roads, snow-covered roads and indoor floors. For every wheelchair, the velocity driving forward is selected manually from three ranges: a low range (3.0 km/h), a middle (4.5 km/h) and a high range (6.0 km/h). Steering, running and braking the wheelchair are done easily by a control stick attached to the arm rest. The running direction and velocity are determined by the slant and angle of the stick. If the control stick is released or returned to the neutral position, the brake is applied automatically to the wheels by an electromagnetic system.

When the wheelchair is driven on icy and snow-covered roads, it is very important that the driving wheel rotates stably without slipping. Therefore, the slipping tendency of the driving wheel was evaluated in this experiment. The slip ratio is defined as the relationship between the actual velocity and the theoretical velocity. The actual velocity $V_c(t)$ is obtained from the acceleration of the wheelchair measured during driving. The theoretical velocity $V_t(t)$ is calculated from the rotation of the motor, the total reduction ratio and the diameter of the driving wheel. The slip ratio $K(t)$ at time t from the start is formulated as Eq. (1).

$$K(t) = \begin{cases} -\frac{V_c(t) - V_t(t)}{|V_t(t)|} & |V_c(t)| < |V_t(t)| \\ 0 & |V_c(t)| = |V_t(t)| \\ -\frac{V_c(t) - V_t(t)}{|V_c(t)|} & |V_c(t)| > |V_t(t)| \end{cases} \quad (1)$$

In Eq.(1), $K(t)=0$ means that the wheel does not slip, $0 < K(t) < 1$ means the degree at which the wheel is slipping, and $K(t)=1$ means that the wheel slips completely. In addition, $-1 < K(t) < 0$ means the degree to which the wheel slides by inertia, and $K(t) = -1$ means the wheel slides completely and locks up the rotation. Thus the ability to be driven on snow-covered roads can be evaluated from the measurement of the slip ratio of each wheelchair.

To measure the slip ratio, an acceleration transducer (AS-TG type, Kyowa Electronic Instruments Co., Ltd., Japan) was mounted under the seat. During driving, the acceleration along three axes and the values of the pulse voltage of the motors were measured on line and were recorded in the data analyzer (DAA-110, Kyowa Electronic Instruments Co., Ltd., Japan). Five pulses of voltage were generated per one rotation of motor. The total reduction ratio of rotation of the wheel to rotation of the motor is 33.5, and the diameter of the driving wheel is 390 mm. Driving tests were carried out on icy roads, snow-covered roads and indoor floors. The low (3 km/h) and high (6 km/h) range were used as the velocities of the wheelchairs. A normal tire and a tire with deep tread for muddy and snow-covered roads (winter tires) were both investigated.

4. Experimental Results and Discussion

4.1 Driving test on indoor floors

In comparisons of drivability involving starting and braking on indoor floors, differences among the wheelchairs did not appear.

4.2 Driving test on snow-covered roads

Snow-covered roads were produced outdoors in the winter season. The drivability was tested on a flat road and an uphill road with a gradient of 1/20. In addition, a driving test on fresh snow was carried out. The outdoor temperature for the test was about -5°C . From each test, it was confirmed that the drivability of the FF type of wheelchair was improved over that of the FR and FC types.

4.3 Driving test on icy roads

To test the drivability on roads with a severely frozen surface, a slope of icy road was made indoors with the cooperation of the Cold Region Housing and Urban Research Institute, Hokkaido Prefecture. Figure 2 shows a wooden slope with a 10% gradient covered with ice plates. The uphill test and start test were carried out on the icy slope. The room temperature for the test was 20°C and the ice temperature was -2°C . Because the surface of the ice was melting, this test was carried out under severe conditions when it is easiest to slide. The uphill test on the icy road was carried out after running on wooden plates

Table 1 Uphill distance on an icy slope

Types of wheelchairs	Velocity (km/h)	Normal tire (m)	Winter tire (m)
FC Type	3	0.5	0.5~0.8
	6	1.0~1.7	0.8~1.8
FR Type	3	1.5	0.5
	6	2.0	1.2
FF Type	3	1.7~1.8	1.2~1.5
	6	2.0~2.7	1.7~2.0

Table 2 Starting ability on an icy slope

Types of wheelchairs	Velocity (km/h)	Normal tire	Winter tire
FC Type	3	D	D
	6	D	D
FR Type	3	B	A
	6	D	D
FF Type	3	A	C
	6	B	D

Fig. 2 Test slope of icy road

2.5 m below the slope. Three trials were done with each wheelchair. No wheelchair, however, could drive 3 m over the uphill slope. Therefore, the uphill distance achieved was measured. Table 1 lists the results. The uphill ability of the FF type was clearly superior to that of FC type and FR type. The FC type could not run uphill, because its front free casters were turned aside easily by the slight bumpy surface. After each type slipped while going uphill, they could not climb any more further because of hydroplaning. The uphill distance at a velocity of 6 km/h was longer, because the approach velocity was higher. The FF type equipped with a normal tire at lower air pressure, which widened the area of traction, could be driven over the hill.

The start test on icy roads was also carried out using a flat region below the slope. Table 2 shows the results. In the table, a mark of "A" indicates that the wheelchair started without slipping, "B" indicates that it climbed although the driving wheel slips immediately after the start, "C" indicates that it did not climb because of slipping, although it started, and "D" indicates that the wheelchair cannot be controlled due to slipping. Clearly from this table, the drivability of the FF type with normal tires was better than the other types.

4.4 The slip ratio during driving

The variation of slip ratio measured at lower velocity (3 km/h) from start to stop on indoor floor is shown in Fig. 3. These data are the mean values of both driving wheels. Every wheelchair showed stable driving with $K(t)=0$. At a velocity of 6 km/h, the braking ability of the FF type was better than that of the FC and FR types. The slip ratio at a velocity of 3 km/h on snow-covered roads is shown in Fig. 4. The differences among the wheelchairs are clear. The FC type slipped at the start. The FF type drove stably without slipping. Figure 5 shows the drivability at a velocity of 6 km/h on the snow-covered road. Every

Fig. 3 Slip ratio at a velocity of 3 km/h on floor

Fig. 4 Slip ratio at a velocity of 3 km/h on snow-covered road

Fig. 5 Slip ratio at a velocity of 6 km/h on snow-covered road

type drives with a constant slip ratio after the start. Upon braking, the FF type stopped and barely slipped. Thus, the drivability can be evaluated by the quantitative data provided by the slip ratio. On snow-covered roads and icy roads, the drivability of the FF type was improved compared to that of the FR and FC types.

5. Computer Simulation

5.1 Method of simulation

We investigated a computational method to simulate the drivability of electric wheelchairs as assessed in the snow-covered road experiment. At first, computer models of the FR and FF types were constructed three dimensionally, and a human model was constructed independently. After unified models were made from the human model and the wheelchair model, a dynamic analysis was done for driving at constant acceleration. The slip ratio was evaluated for various road conditions. Conditions for dry, wet, snow-covered and icy roads, were entered as friction coefficients between the wheels and the road surface.

A software package from DADS (Dynamic Analysis and Design System; Cybernet Systems, CO., Ltd.) was used in this simulation, which can calculate the dynamics of a multibody system. The theory in this simulation is to calculate the Newton-Euler equation of motion to be satisfied with kinematic constraints with respect to each part of the model. The equation of motion for models is expressed as Eq.(2),

$$H(q)\ddot{q} + \left[\frac{\partial \Phi}{\partial q} \right]^T \lambda = Q \quad (2)$$

where a set of generalized coordinates q is defined as Eq.(3).

$$q = [x, y, z, e_0, e_1, e_2, e_3]^T \quad (3)$$

The terms e_0, e_1, e_2 and e_3 in Eq.(3) are Euler parameters and indicate a set of orientative generalized coordinates on each part. The Euler parameters are defined as follows:

$$e_0 = \cos \frac{\chi}{2} \quad (4)$$

$$e = \begin{bmatrix} e_1 \\ e_2 \\ e_3 \end{bmatrix} = u \sin \frac{\chi}{2} \quad (5)$$

The term $H(q)$ in Eq.(2) is the matrix of mass and inertia and is expressed by Eq.(6),

$$H(q) = \begin{bmatrix} M & 0 \\ 0 & 4G^T J G \end{bmatrix} \quad (6)$$

where M is the mass matrix of each part, which is expressed by Eqs.(7) and (8).

$$M = \begin{bmatrix} M_1 & 0 & \cdots & 0 \\ 0 & M_2 & & \vdots \\ \vdots & & \ddots & 0 \\ 0 & \cdots & 0 & M_i \end{bmatrix} \quad (7)$$

$$\mathbf{M}_i = \begin{bmatrix} m_i & 0 & 0 \\ 0 & m_i & 0 \\ 0 & 0 & m_i \end{bmatrix} \quad (i=1, 2, \dots, 23) \quad (8)$$

The term $\mathbf{J}$ in Eq.(6) is the inertia matrix of each part, and $\mathbf{G}$ is the transformation matrix determined by Euler parameter. The terms $\mathbf{M}$ and $\mathbf{J}$ are determined by modeling. The term Φ in Eq.(2) indicates kinematic constraints for each part, which depend on joint configuration. For example, a spherical joint is defined as the condition that a point on one part always coincides with a point on another part during motion. Equation (9) describes the condition of kinematic constraints. Equation (10) is used for a velocity analysis as the first derivative of Eq.(9), and Eq.(11) is used for an acceleration analysis as the second derivative.

$$\Phi(\mathbf{q}, t) = 0 \quad (9)$$

$$\frac{\partial \Phi}{\partial \mathbf{q}} \dot{\mathbf{q}} = 0 \quad (10)$$

$$\frac{\partial \Phi}{\partial \mathbf{q}} \ddot{\mathbf{q}} = \gamma \quad (11)$$

The term γ in Eq.(11) is derived from the equation for the acceleration of constraint. The second term on the left side of Eq.(2) means that a infinitesimal displacement $\delta \mathbf{q}$ is satisfied with kinematic conditions when time is fixed in Eq.(9). The term λ in Eq.(2) is the Lagrange multiplier vector. The term $\mathbf{Q}$ is generalized force, expressed as Eq.(12),

$$\mathbf{Q} = \begin{bmatrix} \mathbf{F} \\ 2\mathbf{G}^T \mathbf{n} + 8\dot{\mathbf{G}}^T \mathbf{J} \dot{\mathbf{G}} \mathbf{p} \end{bmatrix} \quad (12)$$

where $\mathbf{F}$ is the applied force on each part, $2\mathbf{G}^T \mathbf{n} + 8\dot{\mathbf{G}}^T \mathbf{J} \dot{\mathbf{G}} \mathbf{p}$ is moment and coriolis, $\mathbf{n}$ is the applied moment on each part, and $\mathbf{p}$ is the Euler parameter vector.

From the proceeding equations, if the initial conditions for $\mathbf{q}_0$ and $\dot{\mathbf{q}}_0$ are given, the equation of motion can be solved numerically. Then, $\mathbf{q}$ and $\dot{\mathbf{q}}$ are determined so that these values satisfy the constraints of Eqs.(9) and (10).

5.2 Modeling of a wheelchair and a human body

Geometrical models of the FR and FF types of wheelchairs were constructed three dimensionally. Each model is composed of thirteen parts listed in Table 3. The frame is composed of foot plates, a seat back, a seat and arm rests. All parts were modeled with a rigid body element. The required mechanical properties for each part are the values of mass, center of gravity, moment of inertia, and the joint configuration between parts⁽⁴⁾. At first, the geometry and the mass of each part were determined by the measurements of actual wheelchair parts. The reference coordinate of each component was defined in a world coordinate of the wheelchair model. The origin was located in the center between the driving wheel

Table 3 Mass of wheelchair parts

Part	Mass (kg)
Frame (FR type)	24.5
Frame (FF type)	29.0
Battery	15.0
Caster wheel	1.8
Drive wheel	2.7
Caster	1.2
Motor	5.5
Swing	1.2

Fig. 6 Model geometry of wheelchair

and the caster wheel, as shown in Fig. 6. The driving direction was defined as a positive direction along the x axis. The distance between the driving wheel and the caster wheel in the FF type is 100 mm longer than in the FR type. The position of the center of gravity and the position of a joint in each part were determined on each reference coordinate. The moment of inertia was calculated for each part divided by elements of simple geometry and was converted into the moment of inertia on the center of gravity from the theory of parallel axes. Connections between the driving wheel and motor, the caster wheel and caster, and the swing arm and frame were modeled as rotational joints. Connections between the frame and battery were modeled as rigid fixations. Rigid coupling was used between the caster and frame, because only straight driving was done in this simulation. The spring constant between the swing arm and frame is 44.1 KN/m. The damping coefficient is 1.6 KNs/m. The vertical stiffness of the tires is 60 KN/m. These values were also measured on the wheelchair.

The human body was modeled with respect to each part in the same manner as the wheelchair (Fig. 7). The values of mass and geometry for each part of the body were determined from Ref.(5). These data are listed in Table 4. The total mass of the human body was taken as 56.2 kg, which is an average value for elderly men⁽⁶⁾. In this model, the angle of the pelvis and thorax was 15° from the z axis. The angle of the upper leg was 4° from the x axis, and the lower

Table 4 Mass of human parts

Part	Mass (kg)
Upper leg	5.6
Lower leg and foot	3.5
Pelvis and thorax	27.9
Head and neck	4.4
Upper arm	1.5
Forearm and hand	1.3

Fig. 7 Model geometry of human body

Fig. 8 Unified model of wheelchair with rear-wheel drive and a human body

Fig. 9 Unified model of wheelchair with front-wheel drive and a human body

Table 5 Friction coefficient as a function of road condition

Road condition	Friction coefficient
Dry	0.6
Wet	0.4
Snow	0.25
Ice	0.1

leg was 25° from the z axis. Each center of gravity was located at the geometrical center of the part. The moment of inertia was calculated from the geometry of the part assuming that the density was constant. Connections between a set of pelvis, thorax and upper arm positions and a set of pelvis, thorax and upper leg positions were modeled as spherical joints, and other connections were modeled as rotational joints.

Unified models were made from the human model and the wheelchair model as shown in Figs. 8 and 9. Figure 8 is for the FR type and Fig. 9 is for the FF type of wheelchair. Connections between the wheelchair and the human body were fixed at five points at the seat, the arm rests (right and left) and the foot plates (right and left).

5.3 Computational procedure

The simulation was carried out under constant acceleration from start. For three seconds from the start, constant torques were applied to the driving wheel. The values of the torques were determined from characteristics of the motor. The motor used in the wheelchair generates 0.686 Nm (torque) at 15 A (current) at a rotation of $2500 \pm 150 \text{ rpm}$. Considering the reduction ratio (33.5) in driving, a torque value of 23.0 Nm at the driving wheel is obtained at the higher velocity. Therefore, torque values of 15 Nm and 30 Nm were selected for this simulation. From the simulation, the slip ratio of the driving wheel was also calculated using Eq. (1). Flat and sloping roads were selected as conditions. According to Ref. (8), the gradient between a sidewalk and a roadway is prescribed to be 8% for a wheelchair to be able to drive smoothly without any trouble. The simulation was done at slopes with gradients of 8% and 4%. Friction coefficients between the wheel and each road were selected as listed in Table 5^{(7),(8)}.

6. Simulation Result and Discussion

The variation in slip ratio $K(t)$ at a torque of 15 Nm is shown in Figs. 10 and 11. Figure 10 and Fig. 11 are the results on dry roads and on snow-covered roads, respectively. These figures represent values 0.1 second after the start and thereby ignore the change of slip ratio at $t=0$. As shown in both figures, the slip ratio of the FF type was slightly lower than that of the FR type. It was therefore confirmed from the

Fig. 10 Slip ratio on a flat, dry road

Fig. 11 Slip ratio on a flat, snow-covered road

Fig. 12 Velocity on a flat, snow-covered road

computer simulation that the FF type improved drivability regarding slips on snow-covered roads. The variation in velocity on snow-covered roads is shown in Fig. 12. The velocity increased linearly from the start.

The variation in the slip ratio for an uphill drive at a gradient of 8% is shown in Figs. 13 and 14. Figure 13 and Fig. 14 are results on dry roads and snow-covered roads, respectively. In the both figures, the slip ratio $K(t)$ of the FF type was lower than that of the FR type. Although the figure is not shown, at a constant torque of 30 Nm, the slip ratio of the FR type on dry roads was slightly lower than that of the FF type. On snow-covered roads, a difference in the slip ratio between the FF type and the FR type is not

Fig. 13 Slip ratio on a sloping, dry road (gradient=8%)

Fig. 14 Slip ratio on a sloping, snow-covered road (gradient=8%)

apparent, and both slip ratios were close to 1.0. From these results, for driving on a road with a smaller friction coefficient, a larger slip ratio was observed for each model. The FF type was effective on a snow-covered road. Although no figure is shown, the result on an icy road was $K(t) \approx 1$ for each wheelchair, which is the value associated with complete slipping.

It was expected that the slip ratio of a wheel was greatly influenced not only by the location of the driving wheel but also by the center of gravity of the unified wheelchair/human system. Therefore, the center of gravity of the model including a human body was calculated from center of gravity of each part and from $\mathbf{MR} = \sum_i m_i \mathbf{r}_i$ ($i=1, 2, 3, \dots, 23$; $\mathbf{M}$ is the mass of wheelchair/human system, $\mathbf{R}$ is the center of gravity of the wheelchair/human system). As a result, the position with respect to the driving wheel is 0.198 m for the FF type and 0.193 m for the FR type. The center of gravity of the FR type was closer to the driving wheel.

7. Conclusion

In this work, three types of electric wheelchairs were tested for drivability. The drivability of the FF type (front-wheel drive) was better than that of either the FC or the FR type (rear-wheel drive) on winter

roads. In addition, a computational method using a three-dimensional model was proposed to simulate the drivability of each electric wheelchair. It was also confirmed from the computer simulation that the slip ratio of the FF type was less than that of FR type on a snow-covered road. In the future, we will investigate the effect of center of gravity and variation in torque and steering characteristics of the wheelchair and will design a wheelchair with the most suitable structure for outdoor use during winter.

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