IATSS Research 34 (2010) 48–54

Contents lists available at ScienceDirect

IATSS Research

journal homepage: www.elsevier.com/wps/locate/iatssr

Evaluation of physical load of hand-rim wheelchair propulsion on barrier-free model courses

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ARTICLE INFO

Keywords:
Barrier-free
Wheelchair
Physical load
Sidewalk
R–R interval time

ABSTRACT

The aim of this study was to examine the effect of sidewalk developments on the physical load of hand-rim wheelchair propulsion using a barrier-free model course. Non-wheelchair users performed wheelchair exercise tests and R–R interval time, discomfort rating, and postural changes of seating were measured. As a result, due to excessively heavy load on certain parts of the body during active propulsion on the sidewalk, it was shown that barrier-free developments did not lead to a reduction of physical load. The results suggest the importance of a well-balanced barrier-free sidewalk design that takes into account the individual character of the wheelchair user's seating posture and physical load at the time of maneuvering. In addition, it is shown that the reduction of physical load can be considered as an effective method of evaluation.

1. Introduction

The barrier-free transportation law came into force in Japan in 2000, and the groundwork for a “scheme for smooth movement” has been laid. This recent barrier-free measure is gradually expanding as a cause for upgrading all transport facilities, including public facilities. However, the further progress of barrier-free measures depends on conditions, including investment priorities, which are influenced by financial constraints, developmental priorities and stage plans. In addition, barrier-free measures and their evaluation methods are currently progressing in a situation similar to “trial and error.”

As to facility evaluations for the progress of barrier-free measures, comprehensive evaluations by their users have been reported. These evaluations include the evaluations of facilities, individual technology, economy, physical conditions, financial load and amenities [1–9]. In recent years, much study has been conducted into evaluations regarding cost benefits and surveys of awareness, but almost no user-centered evaluation has been conducted into the progress of barrier-free measures.

Recently, efficacy and efficiency are not the only factors to be sought in road-infrastructure improvement, but we are also making plans on how to evaluate the human-centered environment which is built with consideration of the interface between vehicles and people. When we create a barrier-free space, we should especially consider the characteristics of people who have some kind of impairment, people who assist these people and the wheelchairs which are used to support disability. We must also reduce the physical load of impaired people as much as possible and we must evaluate the efficacy of a user's psychological comfort.

For wheelchair users, barriers on roads limit the possibilities of carrying on their daily social life, increase their physical load unnecessarily and become one of the main causes worsening their impairment [10–12]. For instance, not only the frequency of outings by wheelchair users is limited but also the distance they go is limited, depending on how much physical load, caused by the wheelchair, they can bear. The existence of a barrier-free environment is a key issue for reducing their physical load.

The heart rate has been used in various fields as an indicator of physical load. In addition, the heart rate has also been studied systematically as an indicator for objective assessment. The reasons for its use are because of: the compactness of the measuring device, as it is light, thin and small; the possibility of recording for a continuous and a long period of time; the smallness of the impact on the subject of experiments; the ease of any analysis using computers. Kroemer and Grandjean [13], for example, have written about their research findings using the heart rate as an indicator.

If the creation of barrier-free spaces on roads can expand the mobility range of a wheelchair and if this can be related to the reduction of the user's physical load, then the evaluation of the promotion of barrier-free spaces will be established as an evaluation method for facing up to the reduction of the user's functional restrictions and it should be given recognition as an effective and important objective indicator.

This study was conducted on barrier-free model courses, and various kinds of road conditions were chosen in order to evaluate the effectiveness of road improvement for creating barrier-free spaces. As indicators of physiologic load on wheelchair users, changes in heart rate, physical pains and their sources and the changes in their wheelchair-seating posture were studied. Furthermore, discussion was held on the evaluation of the connection between road environment and physical load caused by the promotion of barrier-free spaces.

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doi:10.1016/j.iatssr.2010.06.001

2. Method

In order to study the physical load on the wheelchair user, experiments were performed on conditions of with/without barriers on up/down slopes by measuring R–R interval time, seating posture, and source of physical fatigue. After measurement, the data was analyzed with Statview's statistics and analysis software program. R–R interval times, seating posture, and strength of grip were analyzed on each condition, and a comparative study was conducted. Also, the relationship between physical fatigue and the varying times of occurrence was analyzed.

2.1. Procedure and conditions of the experiment

All of the subjects received explanations about the purpose and the detailed procedures of the experiment individually before the experiment took place. A heart rate monitor was put onto the subjects and the experiment began according to a schedule. At least 30 min rest time was given to each subject during the experiment between each road condition.

2.2. Road conditions for traveling with the wheelchair

2.2.1. Traveling conditions with and without barriers

Fig. 1 shows the road used in this experiment for the wheelchair to travel on. This road was selected from the barrier-free compare-and-experience courses which are administrated by the Kinki Technical Office of Kinki Technical Management Department in the Ministry of Land, Infrastructure and Transport. The one-way distance of the road course used in this experiment was 100 m and the prolonged distance was approximately 200 m. The course "with-barriers" was called "a typical course with some inconvenience for traveling", and it was set up with a slope, ups and downs, a rise with a manhole, a loading area for vehicles and an area with an unleveled road surface. The road width was 4.0 m and a wheelchair could maneuver through it. The "barrier-free" course is called "a desirable barrier-free course." The road width was 4.0 m and the road surface was flat. The road had an average sideways gradient of 1.2%. The area going up and down on the road "with-barrier" had an average ascent of 2.1%. There was no impediment for wheelchairs set in the area going up and down on the "barrier-free" course. The average ascent of the road was 1.0%.

The experiment began after approximately 30 min of practice on how to control the wheelchair. The experiment was conducted in the order of: (1) road conditions of "a typical course with some inconvenience for traveling" (hereinafter referred to as "with-barrier") and "a desirable barrier-free course" (hereinafter referred to as "barrier-free"), (2) road conditions with a slope, and (3) road conditions with different levels. For both "with-barrier" and "barrier-free" courses, courses going-up and going-down were set, and the subjects went up and down 4 times in each direction. This was done randomly and continuously.

2.2.2. Travel conditions with different gradients

Thirty minutes before the experiment into traveling on slopes was started, video cameras and road signs were set at designated places. As shown in Fig. 2, the gradients of slopes were 5%, 8% and 12%, and the travel distances for the slopes were 12.7 m, 7.0 m and 4.7 m respectively. The 5% gradient had a 1.5 m-flat area. The width of each road was 1.5 m. The subjects traveled on wheelchairs in the up and down directions for 3 rounds, and they took 10 min rest after each round.

2.2.3. Travel conditions with different height levels of road surface

Fig. 3 shows that the difference of levels between the sidewalk and road was divided into four heights at 0 cm, 1 cm, 2 cm and 3 cm. In order to make comparisons among the four conditions, the wheelchair made a total of two round trips on each road condition. The second round of each road condition was traveled in a direction opposite to the first round. The experiment was conducted over a total of 8 road conditions–4 conditions for the different heights and 2 conditions for each round–and the subjects traveled 5 times for each road condition consecutively. The heart rate of each subject during maneuvering the wheelchair was analyzed by video recordings, and the instant impact on the subjects was evaluated in order to study their physical load over the rises.

2.3. Measuring instruments and conditions

2.3.1. Measuring the R–R interval time

As shown in Fig. 4, electrocardiography (ECG) is constituted of high and low heartbeats called P, Q, R, S, and T, and the highest spike is R. The R–R interval time is the time between one R beat to the next R

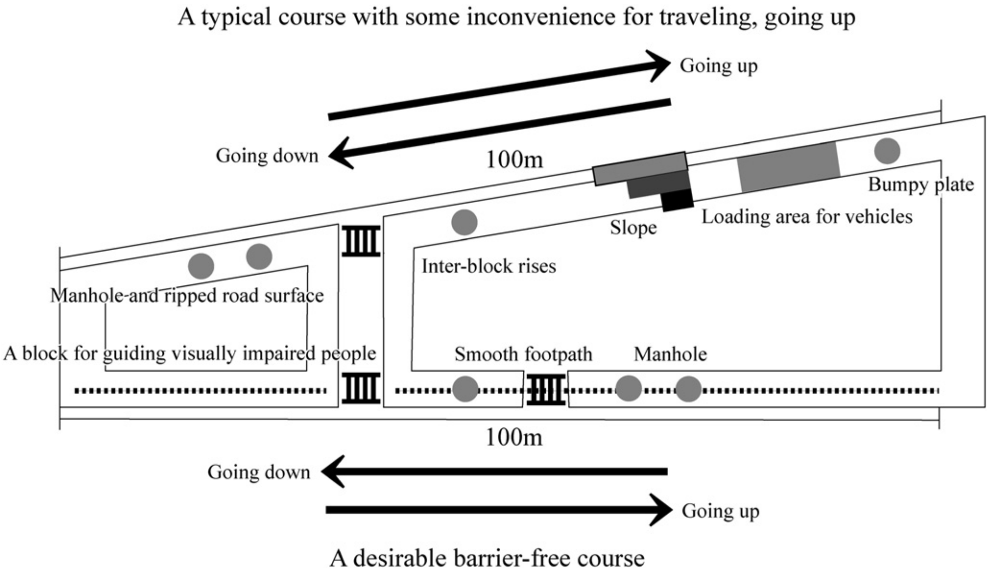

Fig. 1. Travel courses going along up and down conditions.

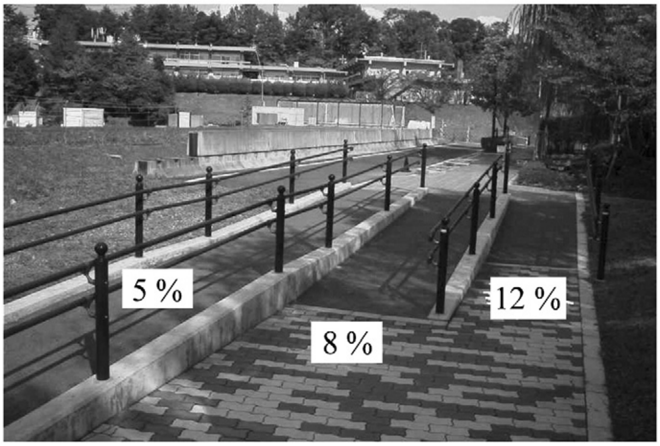

Fig. 2. Travel course with slopes.

beat. When the time between beats becomes shorter, it means that the heartbeat has become faster, therefore, indicating that the heart rate has become high with physical load. A shorter R–R interval time indicates greater physical load.

R–R interval time variability was measured by a portable instrument. This instrument was used in order to minimize the physical load on the subjects. The instrument was made up of two devices—a transmitter and a receiver. The transmitter part (Polar: Wear Link 31C) was 3.7 cm (L) × 6.2 cm (W) in size and incorporated a transmitter in a chest-wear-type electrode-belt. The detected heart beat signals were radio transmitted. The receiver part (Polar: S-810) was a wrist-watch type, and the transmitted signals were recorded to its internal memory.

In the preparation room for the experiment, the epigastric region of each subject was cleaned with alcohol cotton to attach the heart rate monitor, and a band was fixed tight to the body of the subjects. Measuring conditions for R–R interval time were set and the transmitter and the recording device were checked. The receiver part was fixed to the dominant hand of the subject in the same way as a wrist-watch. The recorded data in the memory was loaded into a personal computer by means of a special software program (Polar: Precision Performance) and then analyzed.

2.3.2. Subjective evaluations on the source of fatigue and the strength of grip

Physical fatigue and its source during maneuvering the wheelchair were examined. The body site was categorized into 18 parts, and the sheet was designed so that the time and the place of the occurrence of physical complaints were easily and clearly recorded. Subjective evaluations were made for lassitude and pain in the 18 categories. While maneuvering the wheelchair, each subject reported on symptoms and the source of pain and/or tiredness to assistants of the experiment, and the assistants recorded these complaints and the duration from the start of the experiment.

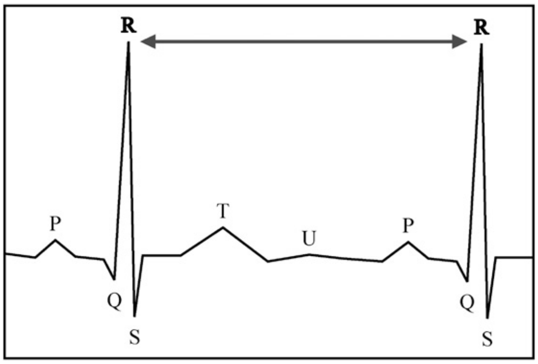

Fig. 4. Chart curve of ECG.

The strength of subjects' hand grip was measured before and after travel in order to use it as an indicator of muscle fatigue when using wheelchairs. The instantaneous strength of the hand-grip was measured with a regular-sized grip dynamometer (Tanita: Hand Grip Meter 6103), twice for each hand, and this total of 4 measurements was conducted for each subject before and after travel. Each subject gripped the dynamometer with the second joint of the index finger almost at a right angle to the meter, and the measurement was conducted with the subject's legs open to make a comfortable posture and with his arm hanging vertically.

2.3.3. Measuring the seating posture

A hand-rim wheel chair (Japanese Industrial Standard) was used in order to conduct continuous measurement of the wheelchair-seating posture of the users, and three places–the external auditory meatus, the eighth rib and the iliac crest–were marked on the left side of the subjects and the wheelchair as a basis for measurement. The shape of the marker was a round one (diameter 5 mm), and it was placed on body-parts where it could be identified in a video image (see Fig. 5).

The wheelchair used in the experiment was remolded so that a video camera could be equipped. A metal arm was fixed to the wheelchair in order to film parts of the body from a certain distance constantly and to prevent movement of the video camera when the

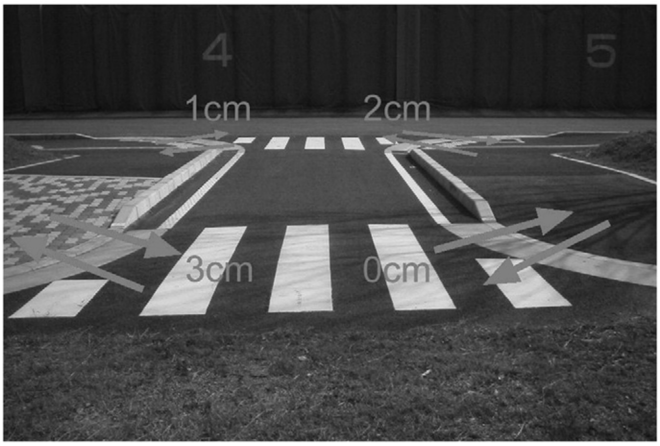

Fig. 3. Travel course with height differences.

Fig. 5. Sample of wheelchair used in the experiment.

wheelchair maneuvered over different height levels of the road surface. The lens of the video camera (Sony: DCR-PC120) was a 37 mm wide-angle lens (Sony: VCL-0437H), and the camera was set to the side of the wheelchair so that the wheelchair and the subject could be monitored through the same frame. The chair-arm and some parts on the side of the wheelchair were removed since they shielded part of the subject's body when measurement was conducted from the side of the wheelchair. The video images were taped at 30 frames/s.

2.4. Subjects

The subjects of the experiment were nine healthy male university students. The average age was 22.1 years old (range: 20–25 years old), the average height was 174.2 cm (range: 161.0–179.5 cm) and the average weight was 62.2 kg (range: 51.0–75.0 kg). None of them had been treated for troubles in their upper limbs, back or musculoskeletal systems within a year, nor did they have any chronic complaint. The subjects were not people who use wheelchairs on a daily basis, so they trained for 30 min before the experiments. Also, the subjects were given sufficient explanation regarding this experiment and agreed, on paper, to join the experiment.

3. Results

3.1. Travel time in the barrier-free spaces

Fig. 6 shows the time required for traveling in the conditions of “with-barrier” and “barrier-free” on up and down courses by a wheelchair. The average of travel times (total of 4 times) were: 107.1 s (sd = 6.64) for “with-barrier” on the upward course, 88.7 s (sd = 3.46) for “barrier-free” on the upward course, 80.9 s (sd = 4.5) for “barrier-free” on the downward course, and 76.1 s (sd = 3.89) for “with-barrier” on the downward course. Compared to the conditions of “with-barrier”, the time required for traveling in the “barrier-free” conditions was longer by 106.3% on the downward course and, shorter by 82.8% on the upward course. All of these were acknowledged as $p < 0.01$ in significant statistical difference over a t-test. It was also found that the required time was longer for the conditions of a downward course than for an upward course regardless of whether or not a barrier existed. Furthermore, a learning effect was recognized in this travel by wheelchair, and this implies that the result could be different according to the level of proficiency of operation.

3.2. Physical load in “barrier-free” spaces

Fig. 7 shows a comparison of R–R interval time in the following conditions: “barrier-free”, “with-barrier”, upward and downward courses. The R–R interval times for the heart beats of the nine subjects are shown in the scatter diagram and the points are connected by lines. For the downward course, the relation between “barrier-free” and “with-barrier” is shown as a line $y = 1.0x + 11.3$. Also, as is shown in Fig. 8, the average R–R interval times for the downward course were 633.3 ms (sd = 99.0) for “barrier-free” and 656.1 ms (sd = 103.1) for “with-barrier”, and this shows that the average R–R interval time for the “barrier-free” condition is short and the heart rate of the subjects increases. As the result of a t-test, this was acknowledged as $t = 3.13$ ($p < 0.014$) in significant statistical difference. For the upward course, the relation between “barrier-free” and “with-barrier” is shown as a line $y = 0.86x + 82.4$. In addition, the average R–R interval times were 614.1 ms (sd = 99.9) for “barrier-free” and 609.5 ms (sd = 88.4) for “with-barrier”, and there was no significance statistical difference.

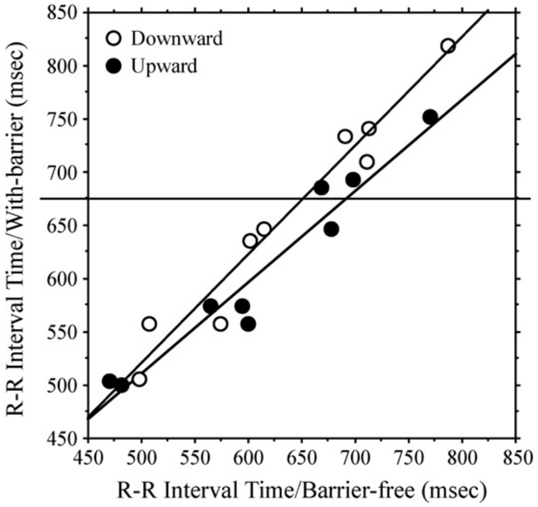

Fig. 7. Comparison of R–R interval time in the conditions with and without barriers.

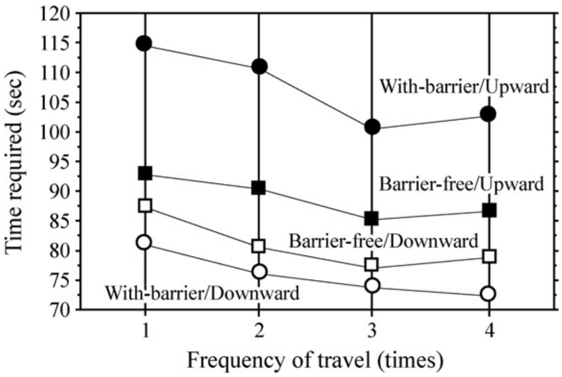

Fig. 6. Comparison of time required for the conditions with and without barriers.

This shows a very interesting result concerning the relationship between road improvement and the physical load in “barrier-free” spaces. For the upward courses, the gradient of the road plays a more affective role in the increase of the degree of physical load on a wheelchair user than conditions regarding whether or not a barrier exists. For the downward courses, it is suggested that the user's heart rate increases and the physical load increases due to an increase of the speed of the wheelchair.

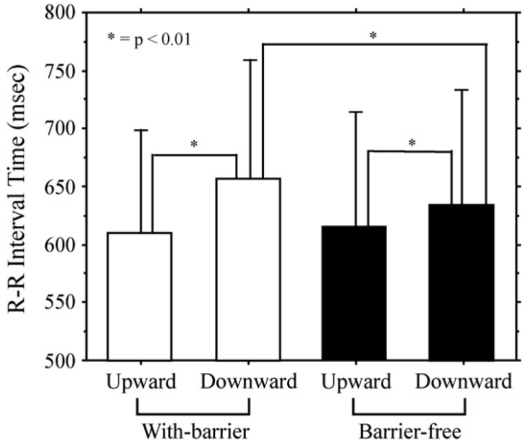

Fig. 8. Average of R–R interval time for each course.

3.3. Road with slope and physical load

Table 1 shows a comparison between the average R–R interval time and the standard deviation of heart rate over conditions of slopes with different gradients. The heart rate of the subjects was different for upward and downward slopes. For the downward slope condition, the shortest R–R interval time was recorded at 12%, next 8% and the longest at 5%. For the upward slope condition, the shortest R–R interval time was the same as the downward condition at 12%, however, the next was 5% and the longest at 8%. On the downward slope, the higher the gradient ratio becomes, the higher the heart rate becomes. For the upward slope, not only the gradient ratio but also the travel distance caused by the different gradient conditions could affect the level of the heart rate.

Fig. 9 shows the relation between the upward and downward conditions with three different gradients from the point of R–R interval time. The plots in the figure show the average R–R interval time for each subject, and the lines and equation forms were estimated according to each condition. As the figure shows, as the level of a gradient increases, the physical load for both upward and downward conditions becomes different. The physical load on the heart rate increases further as the level of the gradient increases in an upward condition.

3.4. Condition regarding different height levels on the road

Fig. 10 shows the physical load by heart rate in a situation where a subject in a wheelchair travels 2 m over the point of a rise on a road in different conditions. For a 3 cm-high rise, when the wheelchair traveled upward, the significant statistical difference of a t-test was shown in comparison to the conditions for other levels. However, there was no significant statistical difference for all levels in a comparison between the upward and downward conditions. When the difference in the height of a level was over 3 cm, the physical load increased for the upward condition.

3.5. Subjective evaluation of physical fatigue and its source

Fig. 11 shows the subjects' physical fatigue, its source and the time at which it was reported by the subjects as they participated in the experiment to study the physical load on a wheelchair user. Even in the cases where a subject made more than one physical complaint, it was recorded as one time. The highest numbers of complaints in order of frequency were in these three areas: shoulders, fingers and arms. The average time taken before this physical fatigue occurred was: 17.0 min for the back, 11.4 min for the shoulder, 12.0 min for the arm, 13.6 min for the wrist and palm, and 19.0 min for the fingers. The shoulders, arms and fingers of the human body seem to be related directly to travel by wheelchair, and the back and hip seem to have a role to support the movement of the shoulders, arms and fingers. Many of the complaints about shoulders and arms were made at a relatively early stage. The complaint about fingers was the last made in spite of the fact that fingers related to grasping and supporting the rim of the wheelchair.

Comparing the instantaneous strength of subjects' grip before and after traveling by wheelchair, the average strength of grip of the left hand changed from 37.4 kg (sd = 4.3) before travel to 35.7 kg (sd = 4.1) after travel, and it changed from 40.4 kg (sd = 5.4) to 39.5 kg (sd = 5.9) for the right hand. A significant statistical difference was noted for the strength of the left hand ($t = 2.34$, $p < 0.05$). The strength of grip lowered greatly for the right hand, but it is thought that this happened because all of the subjects were right-handed, thus the deterioration of muscle strength was small (see also Fig. 12).

Table 1
Average of R–R interval time for each slope.

	Upwards ms (sd)	Downwards ms (sd)
Gradient 5%	634.1 (59.0)	674.6 (76.7)
Gradient 8%	641.8 (65.5)	654.1 (69.6)
Gradient 12%	630.0 (54.6)	647.4 (75.7)

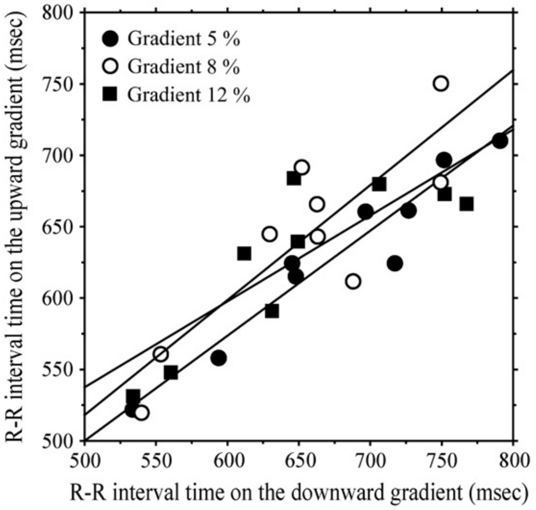

Fig. 9. Comparison of R–R interval time in the conditions with slopes.

3.6. Changes of seating posture

Fig. 13 shows the changes of seating posture at the beginning and end of propulsion when the subjects are operating wheelchairs. The auditory meatus showed the greatest movement on a slope with a 12% degree of ascent. Comparing this to an ascent of 0%, it was 2.8 times longer at the beginning of propulsion and 3.4 times longer at the end of propulsion. According to the results of the t-test, there is a significant statistical difference for both the beginning and end of propulsion at the auditory meatus on the slope with a 12% degree of ascent in comparison to other conditions. In the case of the eighth rib, at the end of propulsion on the slope with a 12% degree of ascent, the statistical difference from the condition of a degree of 8% was 2.2 cm ($t = 2.92$, $p < 0.02$), and it was found to be significant. However, the differences between the beginning and end of propulsion were 0.62 cm at an ascent of 0%, 0.47 cm at 5%, 0.42 cm at 8%, and 1.07 cm at 12%, and the difference was found to be insignificant. These results show that when a wheelchair ascends a slope under the conditions described above, the gravity point of a user's body always moves forward, and the user is controlling the wheelchair in an unnatural posture.

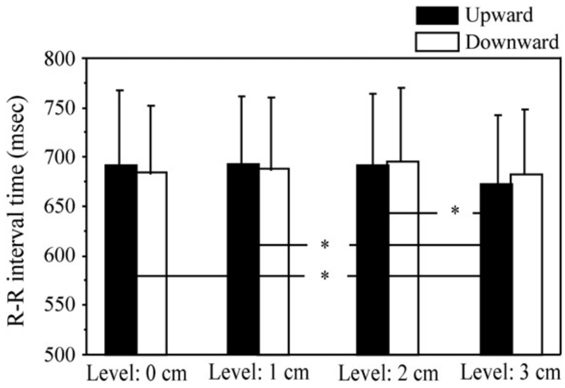

Fig. 10. Average of R–R interval time for each height difference.

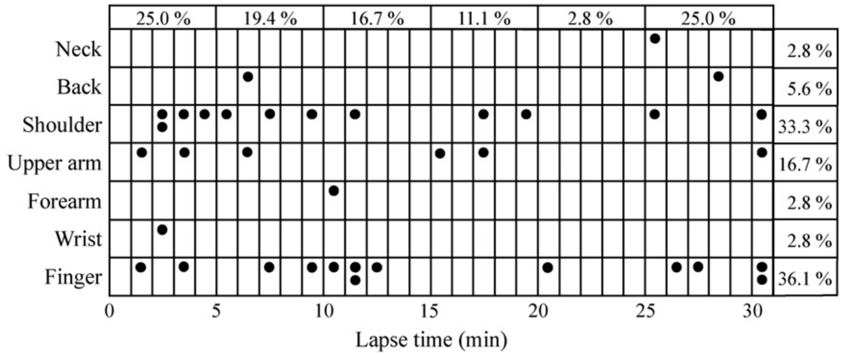

Fig. 11. Relationship between the source of physical fatigue and the time of occurrence.

4. Discussion

The physical load on a wheelchair user was studied on two courses: "with-barriers" and "barrier-free". The study was conducted by measuring the time required for travel, R–R interval time, and hand-grip strength. In addition, fatigue of body parts and changes in seating postures of the user were observed. With this information, an assessment of the relationship between a barrier-free road environment and the physical load of wheelchair users was reviewed.

(1) On a comparison of the "barrier-free" and "with-barrier" courses, the traveling time on the downward condition was longer for the "barrier-free" course than the "with-barrier" course. Also, the result of the R–R interval times was shorter on the "barrier-free" course which indicates a higher heart rate. In addition to the gradient of the downward slope, there was also a sideways gradient which causes greater physical load for the wheelchair user because of the need to control the decent on two directional gradients. It can be said that this is a possible reason for the increase of heart rate. In the case of the downward course, the increase of heart rate seems to be dominated by the physical load of controlling the wheelchair decent on a slope with two separate directional gradients more than just avoiding barriers on the slope.

(2) R–R interval times became shorter on the downward slope condition as the gradient increased. However, on the upward slope condition, the order of R–R interval times was not the same as the downward slope condition. An 8% gradient on the upward condition marked the longest R–R interval time which indicates the least physical load. As the gradient increased, the order of comparative physical load between the upward and downward conditions became different. Also, regarding changes of seating posture on the upward slope condition, the largest movement of the center of gravity of the user's body was noted at the highest gradient of 12%. However, the R–R interval time on the upward condition was longest at a gradient of 8%, and the difference of seating posture changes between 8% and 12% was great. In this case of the upward condition, an increase of gradient does not equal a higher physical load. The increase of physical load is related to a combination of distance and gradient.

(3) Subjective evaluations of muscle fatigue indicate that muscle fatigue was felt most in the shoulders, arms and fingers of the hands of the users. This is because, as the seating posture during traveling shifted forward and the user had difficulties in holding the hand-rims, the wheelchair was operated at the front of the rims which caused the users arms to open sideways. This unnatural posture seems to cause muscle fatigue in parts of the body of the user. The fatigue of fingers seems to be related to the degree of difficulty in gripping the hand-rims. The size of the hand-rims for the wheelchair used in this experiment was 1.8 cm diameter and it was made of plastic. These were too thin to grip firmly and easy to let slip, and this seems to be related to the load on the fingers. These factors caused a heavy load on shoulders, arms and the fingers, and this led to a decrease of gripping power by the user.

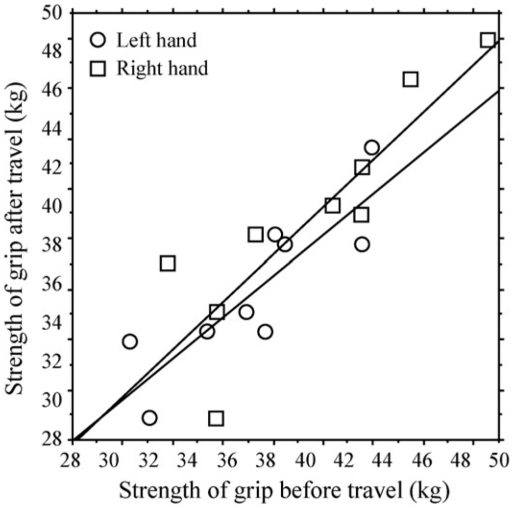

Fig. 12. Comparison of strength of grip.

5. Conclusion

In this experiment, it was thought that a "barrier-free" course would reduce physical load in comparison to a "with-barrier" course. However, there was no reduction of physical load on the downward condition slope compared to the "with-barrier" course. Moreover, a possibility was revealed that the physical load on the "barrier-free" course became greater than the "with-barrier" course. It was also revealed that the seating posture changes depending on the gradient of the slope, and that the users are forced to maneuver the wheelchair in an unnatural posture. Propulsion of a wheelchair while some parts of the body are feeling some kind of load cannot lead to a reduction of physical load.

Concerning transport facilities which are used by people with various kinds of disabilities, it is important to understand their action characteristics, to evaluate sidewalk structures for them, and to decide on well-balanced constructions. Assurance of convenience and safety of traffic access between their homes and destinations for disabled users are necessary. In this regard, construction of a merely partial barrier-free zone has no effect, and a comprehensive barrier-free environment is required.

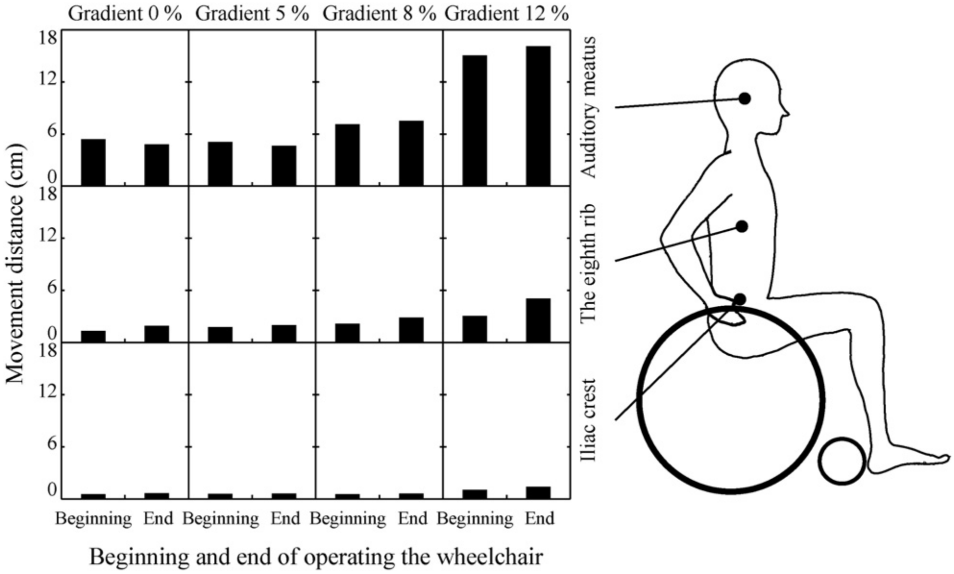

Fig. 13. Movement distance of seating posture for each slope.

The subjects of measurement in this study were people without disabilities. In the future, it will be necessary to take measurements with people who need to use wheelchairs on a daily basis. A further requirement for future study will be to collect data with an increase in the number of subjects and the conditions of measurement.

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