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DEVELOPMENT AND VERIFICATION OF NAVIGATION SYSTEM TO SUPPORT WHEELCHAIR USER ACTIVITY IN URBAN AREAS

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ABSTRACT

Based on a previously developed prototype system, a wheelchair navigation system that searches for an optimum route from a current location to a destination has been improved and evaluated. Improvements included applying textures to buildings so that wheelchair users could more easily identify a particular location on a route. In addition, the method used to measure physical burden was improved. Measuring points were increased and changed from a single arm to both arms, and measuring locations were increased. The usefulness of each searched route was verified through two test runs with wheelchair users and a workshop method. Based on these results, we have developed a smartphone version of the wheelchair navigation system.

KEYWORDS

Wheelchair Users, Wheelchair navigation system, Optimum route, Workshop, 3D image

1. INTRODUCTION

The Japanese population is currently declining, and provincial cities are considering compact city planning to limit the expansion of urban centers. Planners hope to encourage residents to move to urban centers and encourage shopping within the urban center by promoting public transportation, such as trains and buses. However, in many provincial urban centers, it is difficult for the physically disabled and their caregivers to enjoy downtown activities due to lack of accessible public transportation, level differences on sidewalks due to poor maintenance and lack of parking lots and toilets specifically suited for the disabled. In contrast, large suburban shopping malls usually have suitable parking and wheelchair-accessible toilet facilities. Consequently, many physically disabled people use suburban shopping malls rather than malls within the urban center. If compact urban environments are to be promoted successfully in Japan, city planning must include infrastructure that allows both able and disabled individuals to enjoy downtown areas safely.

The final goal of this study is to realize an environment wherein able and disabled individuals can move safely in urban centers. This paper describes the development and verification of the usefulness of a wheelchair navigation system.

2. RELATED WORK

The authors have developed a ‘physically disabled person support system’ to support wheelchair users (Izumi, S. et al., 2007; Koga, M. et al., 2014; Inada, Y. et al., 2014; Yoshioka, D. et al., 2015; Inada, Y. et al., 2015). The support system has two functions: a software-based mobility support ‘wheelchair navigation system’ that searches for an optimum route from a current location to a destination and a hardware-based ‘downtown development review support function’ that simulates how burden will be eased for wheelchair users by preparing appropriate sidewalks as welfare town planning review support. This study aimed to identify and address the wheelchair navigation system problems, which has been developed as a trial.

Eguchi-Yairi et al. developed a mobility support tool that calculates and presents a safe and optimum route from a departure location to a destination using a geographic information service (Eguchi-Yairi, I. et al., 2005). Their tool considers traffic volumes, i.e. both vehicles and pedestrians, as well as factors that narrow sidewalk width (e.g. roadside trees and utility poles) to calculate a safe optimum route. However, the physical burden imposed on a physically disabled individual is not considered in the route calculation. Even if the street is wide, a physically disabled person could be subjected to significant burden if the street surface has not been properly maintained or the cross slope is steep. The current study has developed a tool that calculates physical burden for the physically disabled and presents an optimal route with the least possible physical burden.

3. PREVIOUS WHEELCHAIR NAVIGATION SYSTEM DEVELOPMENT

Here we summarize the development process of a prototype model of the wheelchair navigation system. Before the development of the system, we conducted a survey with wheelchair-bound users to collect opinions about features/trends and problems/challenges related to mobility in any urban center. It was determined that participants avoided poorly maintained streets and many sidewalks had cross slopes that required the wheelchair to be pushed with one hand. In addition, wheelchair vibration on poorly maintained streets and front casters being caught by differences in surface level when moving from a pedestrian crossing to a sidewalk were identified as problems. Next, a target area for the system was selected, and the characteristics of downtown locations were surveyed for each street from the perspective of wheelchair users. Part of the urban center (approximately 13.6 ha) of Kumamoto City, Japan, was selected as the target area. For routes in the target area, 72 streets were chosen and surveyed under the supervision of an advisor for the physically disabled. The survey items included the length, width and material of each route, as well as manholes, gratings and poorly maintained sections as barrier factors. Passage-obstructing on-road installations, such as roadside trees, signs and signboards, were also surveyed.

The system was developed as follows: (1) Based on the downtown survey results, a three-dimensional (3D) model of the target area was created. (2) Links and nodes were added to the 3D model, and the survey data was input to the links. (3) An optimum route search algorithm was created. (4) Non-disabled researchers travelled all streets in the target area in a wheelchair to measure muscle activity. Based on the measured muscle activity, a physical burden ratio was calculated, and this information was input to the links. (5) To complete the system, a wheelchair character and interface were designed, a function to be set by an administrator was implemented and a control panel, including the input screen for the departure location, destination, etc., was created.

For optimum route calculation, Dijkstra’s algorithm is used to calculate the shortest logical distance from all routes from a departure location to a destination. Here, logical distance considers fatigue, which is then converted to a linear distance by multiplying the physical distance by a physical burden factor. The physical burden factor is calculated from the muscle activity amount while travelling on actual street in a wheelchair. Targeting 10 m or longer links (224 return routes) to calculate muscle activity, the researchers travelled 5 m in the central part of the target links using a wheelchair. An electromyograph (TeleMyo2400, Noraxon) was used to measure the muscle activity. Muscles were measured at six points on the researchers’ dominant arm (right) (biceps brachii, triceps brachii, anterior deltoid, middle deltoid, posterior deltoid and brachioradialis muscles).

4. CHALLENGES AND IMPROVEMENTS TO PREVIOUS WHEELCHAIR NAVIGATION SYSTEM

The usefulness of the previous wheelchair navigation system was verified by wheelchair users who performed a test run along the selected routes. After the test run, the wheelchair users discussed their experiences in a workshop (WS). The following problems with the system were identified: (1) The buildings in the 3D image do not have textures, which makes it difficult for the user to determine their current location; (2) many sidewalks have cross slope; consequently, the wheelchair tends to tilt (often requiring the user to push with one hand). In addition, data reliability becomes questionable relative to the measurement physical burden when only a single hand is used. Only the central part of each street (link) was measured; however, one street had not been maintained uniformly and its surface was uneven, resulting in questionable data reliability; (3) some wheelchair users may prefer shorter or sidewalk-only routes over those with low physical burden and may avoid streets with uneven surfaces, which can easily make wheelchairs vibrate.

To enhance the practicality of the wheelchair navigation functions, we increased the size of the target area, remodelled the computer graphics (CG) to improve visual quality, measured physical burden in detail and increased the types of navigation routes. Furthermore, we measured the vibration of the wheelchair due to uneven road surfaces on each target street using angle speed sensors, GPS-receivers, etc. attached to the wheelchair. Next, we investigated the relationship between street maintenance and wheelchair vibration. Then, we implemented a test run with wheelchair users and conducted a workshop-type discussion to verify the navigation routes. Finally, based on the results, we developed a smartphone version of the test model of the wheelchair navigation system.

5. TARGET AREA

Due to the addition of one block to the previous model, the target area now comprises 93 streets, 214 nodes and 268 links (Fig. 1). The target area included the Kumamoto Municipal Office, two department stores, shopping arcades and S- and G-streets. Ninety-three streets were selected as the wheelchair routes, and 214 nodes and 268 links (536 return routes) were set by adding new nodes to the 93 streets in the target area. The departure location and destination were a wheelchair accessible/multi-purpose toilet and a parking lot for physically disabled persons, respectively. Then, as with the previous model, the target area element data were input to each link, e.g. a pedestrian bridge, sidewalk distance, number of pedestrians, number of manholes and on-road installations.

6. MEASUREMENT OF PHYSICAL BURDEN

The researchers travelled all routes with 10 m or longer links (186 return routes), excluding intersections and the parking lot entrance, in a wheelchair and measured physical burden using an electromyograph (TeleMyo2400, Noraxon). Differing from the previous model, in this study, eight muscle points on both left and right arms were measured rather than six points on the dominant (right) arm. In addition, the entire street rather than only part of the street was measured. Figure 2 shows the measuring points, and Fig. 3 shows an example of muscle measurement results.

Figure 4 shows the physical burden measurement results for each link. Physical burden is represented by a **color** scale where green is low and red is high. The physical burden of Route A (link 65-3), which had the highest physical burden, was 90,664.16. Compared with the other streets, it has a greater cross slope. The sidewalk tilts obliquely downward to the right in the direction of travel, and a high burden was imposed on the right arm. In general, muscular burden increased on uneven streets with poorly maintained sidewalks. Route B (link 85-50) had the lowest physical burden (1,309.47). Compared with the other streets, it is better maintained and paved with smooth tiles. Based on these results, it was determined that physical burden differed greatly depending on the maintenance and material of the sidewalk. These physical burden measurement results are input to determine the most fatigue-free route (i.e. route with the lowest physical burden) from the current location to the destination. The wheelchair navigation system interface is shown in Fig. 5.

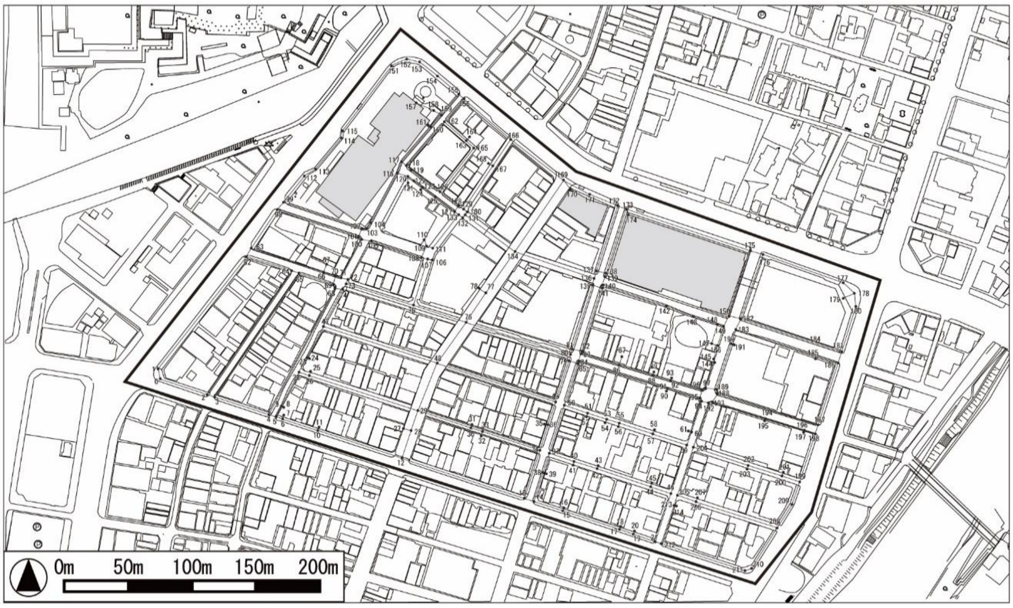
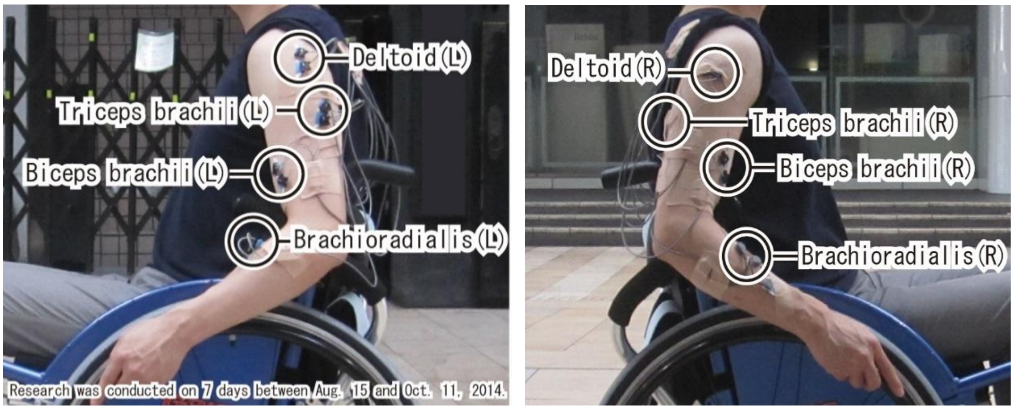


Figure 1. Overview of the target area



Research was conducted on 7 days between Aug. 15 and Oct. 11, 2014.

Figure 2. Physical burden measuring points using an electromyography

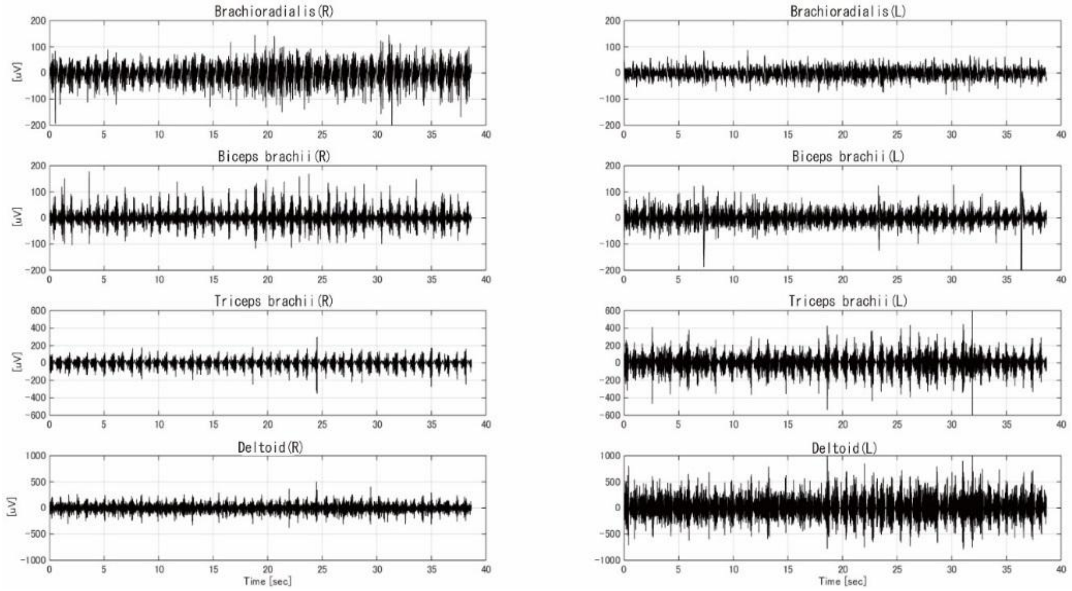


Figure 3. Example of muscle measurement results (eight points on both arms)

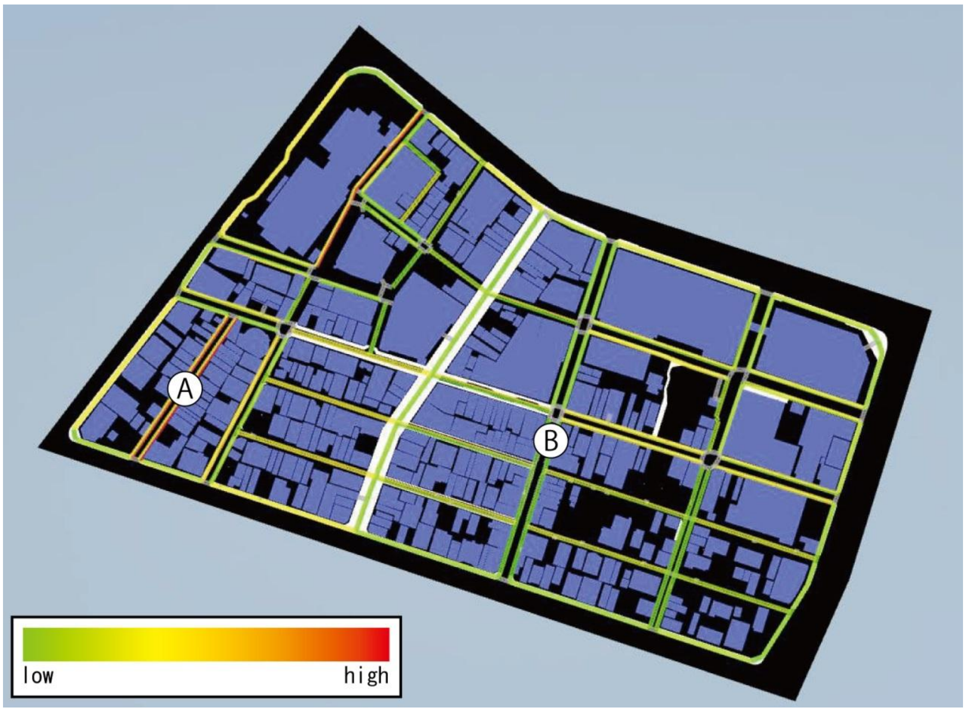


Figure 4. Physical burden measurement results for each link

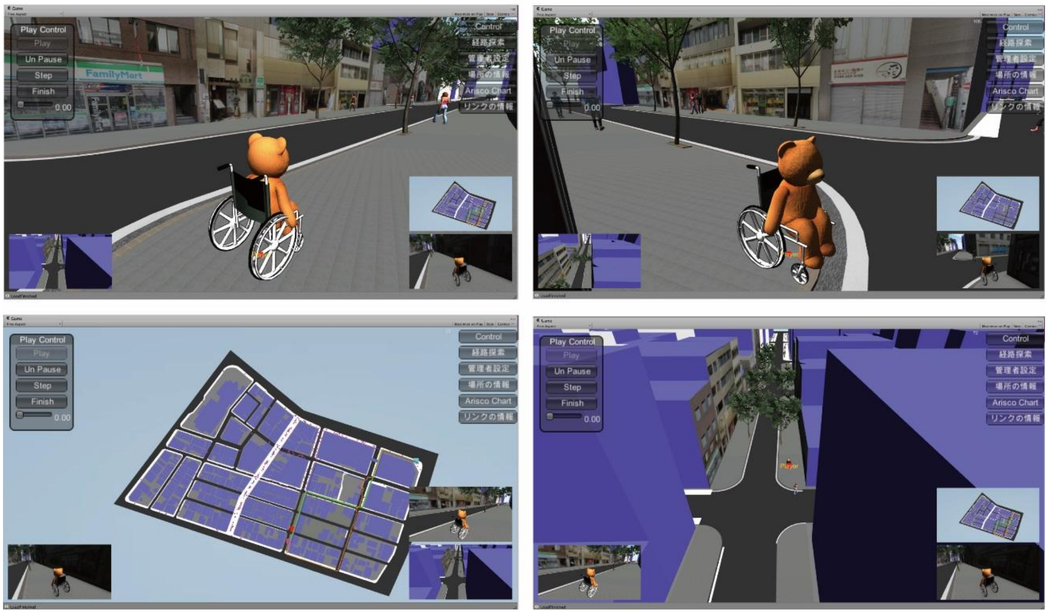


Figure 5. Wheelchair navigation system interface

7. SURVEY OF WHEELCHAIR VIBRATION

It was suggested that wheelchair vibrations produce unpleasant feelings for users. Therefore, we attempted to clarify its reliability by measuring the vibration of a wheelchair moving on the target streets. The researchers travelled all routes with 10 m or longer links (186 return routes), excluding intersections and parking lot entrances, by operating wheelchairs for 11 days between 15th August, 2014 and 27th January, 2015.

For this measurement, we set up an angle speed sensor on each wheel of the wheelchair, a rotary sensor (one pulse/rotation) on the left wheel, and an acceleration sensor, compass sensor, angle speed sensor and GPS receiver (ublox 6T) under the seat (Fig. 6). The measurement results for each route are shown in Fig. 7 and Fig. 8. The route with the highest vibration magnitude was Route A (4,274,362 vibrations, links 76-73). The route with the lowest vibration magnitude was Route B (338.0109 vibrations, links 182-181).

Route A with the highest vibration magnitude is a pedestrian street with many restaurants. This route is very safe due to the wide sidewalks and lack of automobiles. However, the surface is paved with bricks; therefore, wheelchair vibration is high. In addition, it was difficult for the wheelchair users to travel Route A due to poorly maintained sections of the street, which resulted in high physical burden. In contrast, Route B is paved with smooth tiles and is well maintained; thus, the wheelchairs could move easily, which resulted in low physical burden even though its safety is low due to the narrow sidewalk.

Furthermore, Routes C and D also showed low wheelchair vibration magnitude. Both routes are paved with smooth tiles and are main streets for pedestrians. Route D is popular for wheelchair users due to low wheelchair vibration magnitude and low physical burden because it has wide sidewalks running through an arcade in the urban center.

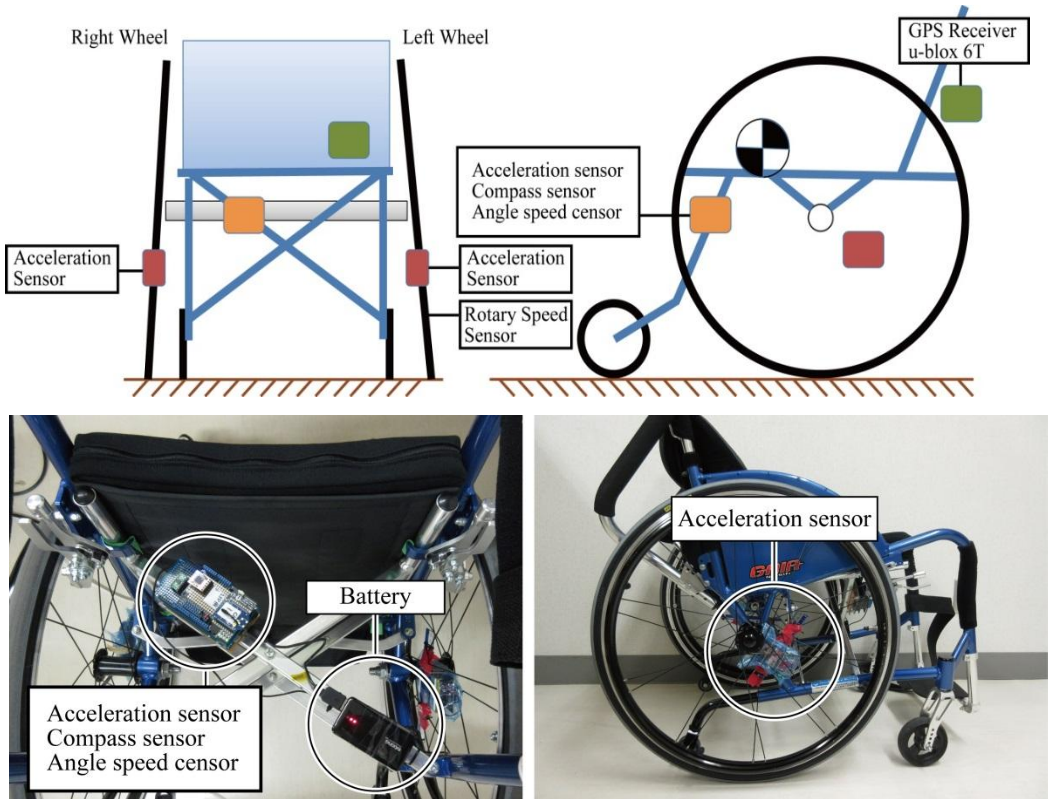


Figure 6. Sensors

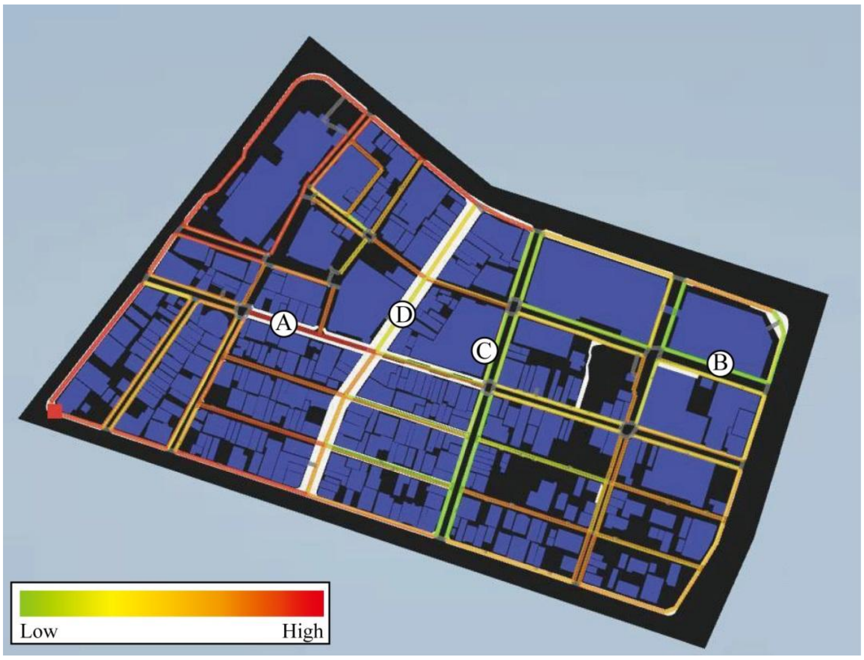


Figure 7. Vibration measurement results

Figure 8. Photographs of measured routes

8. ROUTE SEARCH VERIFICATION

We evaluated the wheelchair navigation system to verify the route search with six self-propelled wheelchair users divided into two groups (Group A and B; Scenario A and Scenario B, respectively) as subjects. The first evaluation was conducted on 25th October 2014, and the second one on 6th December 2014.

In the first evaluation, the wheelchair users travelled the shortest route followed by a route with a low physical burden as a preliminary experiment (feedback on the preliminary experiment is excluded in the study results). Then, the routes favorable to the wheelchair users were determined in a WS discussion.

In the second evaluation, the subjects travelled a route with low physical burden, a sidewalk-only route, and a route chosen by the wheelchair users (one examined in the WS following the first evaluation). Then, the subjects participated in a WS and discussed the routes. Scenarios A and B routes are shown in Fig. 6. Verification results are listed in Table 1.

Scenario A received positive evaluations with regard to reaching the destination in the shortest distance; however, there were concerns that the route included a section where the sidewalk was narrow and crowded, posing some risk to the wheelchair users. In Scenario B, the route diverted on the way from a shopping arcade, and many subjects wanted to pass through the shopping arcade to the end. Some subjects indicated that they preferred a safe route to the shortest one even if it extended the route length.

In Scenario A, the route with low physical burden received positive as well as negative evaluations. This route (Node 126-134) included a steep downward slope. Some subjects felt comfortable travelling down the slope, while others felt the slope presented a risk. Scenario B received lower evaluations than Scenario A because the searched route was complicated and difficult to understand. The route in Scenario B forced the subjects to get off and back on the sidewalk frequently. Consequently, there were many level differences, and the participants were subjected to vibrations frequently. Moreover, more subjects preferred the shortest route.

Concerning the sidewalk-only route, its search result was the same as the shortest route for Scenario A. There was an opinion that high pedestrian traffic at a scramble intersection near a department store posed some risk. Scenario B received positive evaluations because there was no concern about cars coming from behind, allowing the subjects to easily travel. With regard to the routes discussed in the WS, both Scenarios A and B chose the Shimotori shopping arcade (S-street). Although it has high pedestrian traffic, it was evaluated highly because it has a wide fully paved sidewalk.

The evaluation indicated that if the subjects enjoy sports daily and have physical confidence or if they are young males, they tend to choose the shortest or an uncomplicated route and are not particularly concerned about small level differences. However, other subjects tend to be concerned with safety and choose routes with a wide sidewalk or less crowded routes where there is no possibility of collision with pedestrians (wheelchairs move faster than pedestrians). Since vibrations impose a burden on the body, the subjects tended to prefer routes with fewer vibrations. In general, the sidewalk-only route was considered safe; however, utility poles in the middle of the sidewalk and a significant number of signboards obstructed the wheelchairs occasionally. The route chosen by most participants was the shopping arcade, i.e. S-street (Node 139-12). This street does not have a particularly low physical burden value; however, it has the widest sidewalk and is well paved, allowing safe wheelchair travel. It also received positive evaluations because it was under cover, and participants would not get wet even when it is raining. In future, we must develop an algorithm that preferentially chooses such highly evaluated streets.

In general, the results indicate that the system should be capable of searching for the shortest route, routes with low physical burden and sidewalk-only routes.

9. CONCLUSION

To improve the practical application of a previous prototype model of a wheelchair navigation system intended to support accessibility and ease of travel in urban areas, we have addressed problems with the system. The following points summarize the improvements and present suggestions for future work.

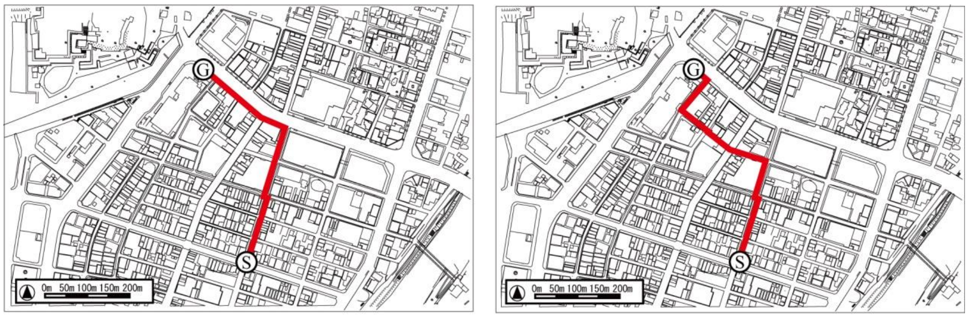
1) To improve the wheelchair navigation system, the target area was expanded, and textures were applied to buildings to help wheelchair users more easily identify specific locations on a route. Thus, we improved the interface by showing a town view.

2) To improve the search accuracy of routes with low physical burden, a more detailed measurement of physical burden was performed. In our previous research, muscle activity of only the user's dominant arm was measured. Thus, accurate muscle activity could not be measured. Therefore, in this study, the muscle activities of both arms were measured. Moreover, total muscle activity for the entire distance of the target link was measured, while in the previous research, muscle activity was measured for only 5 m in the central part of the target link. The obtained data was then input to the disabled support system.

3) By measuring wheelchair vibration on each street of the target route, the relationship between street materials and maintenance was investigated. Although streets paved with bricks look good, the physical burden of wheelchair users is high due to high wheelchair vibration on such streets because wheelchair casters can be caught on the cracks between bricks easily. In contrast, the central streets in the shopping arcade are paved with smooth tiles. Consequently, the physical burden is low due to low wheelchair vibration.

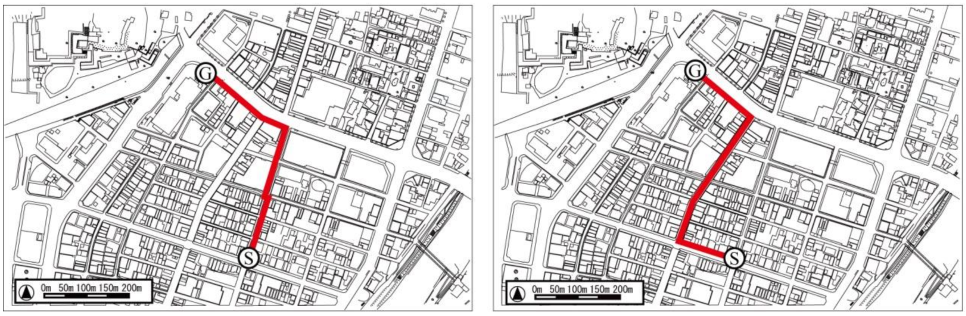
4) The system was improved to include a search system that can select the shortest route, a sidewalk-only route and routes with low physical burden. Then, the usefulness of each route was evaluated through various verifications and many WSs. It was found that many wheelchair users prefer routes with high safety to the shortest route. Therefore, the sidewalk-only route was evaluated as very safe because cars do not approach from behind. Although routes with low physical burden were evaluated to some extent, it was complicated and difficult for wheelchair users to search its route because such routes involve getting on and off the sidewalk and have significant vibration. Therefore, other routes were preferred by many wheelchair users. Many users preferred the route with the arcade in the center of town. This route is safe because it has a wide and fully paved sidewalk. Moreover, this route was highly evaluated because there is no concern about getting wet when it is raining. In future, an algorithm to select such highly evaluated streets is required.

5) The above-mentioned survey result data were reflected in the system to create the smartphone version. To expand the target area further in future, a physical burden measurement method will be proposed using a simple survey method to enhance the versatility of the wheelchair navigation system.



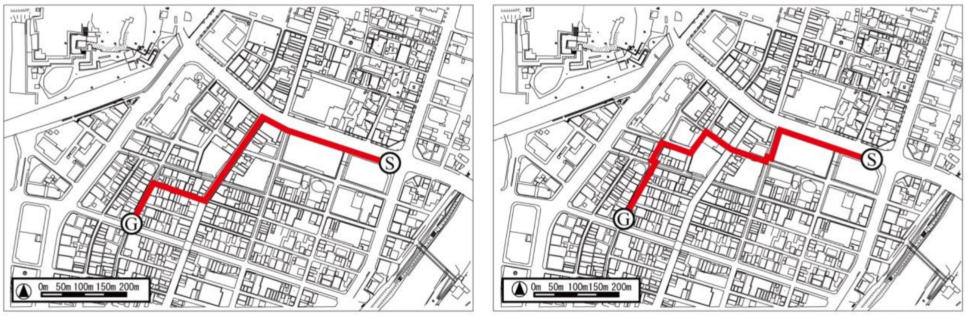
Scenario A:shortest route

Scenario A:route with a low physical burden



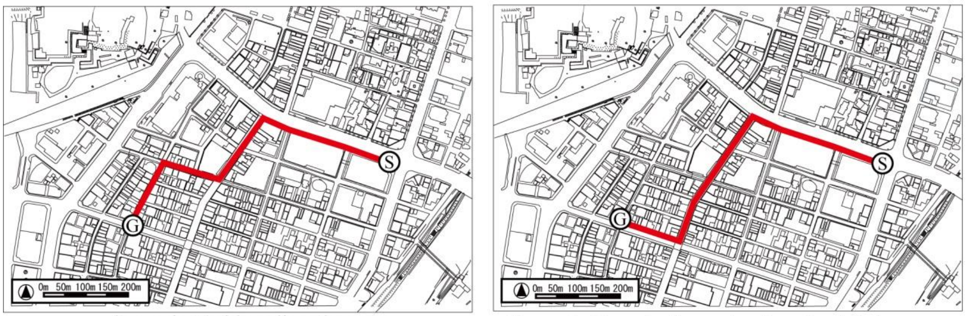
Scenario A:sidewalk-only route

Scenario A:route chosen by the wheelchair users



Scenario B:shortest route

Scenario B:route with a low physical burden



Scenario B:sidewalk-only route

Scenario B:route chosen by the wheelchair users

Figure 6. Results of route Search (Scenarios A and B)

Table 1. Wheelchair users' opinions for each route in the evaluation

Route	**Opinions of Group A (Scenario A)**
Shortest route	▪ Compared with the S-street, the street width was narrower at some spots. ▪ It was good to be able to travel the shortest distance. ▪ It was crowded and risky around Node172. It was hard to travel because of utility poles. ▪ Wheelchair travel was obstructed by utility poles and parking on the sidewalk. ▪ It was crowded and I had to avoid pedestrians. ▪ The sidewalk before the municipal office was wide and easy to travel. ▪ Level differences of the street and pedestrian and vehicle traffic volumes were disturbing.
Route with a low physical burden	▪ Since the wheelchair travelled too fast due to a steep downslope, I had to apply the brakes. That felt risky. ▪ I felt no physical burden, but found shop signboards on the sidewalk obstructive. ▪ As a whole, I felt no upslope. ▪ I wanted to travel the S-street from 134.
Sidewalk-only route (same as the shortest distance)	▪ It was hard to travel because the street was narrow and crowded with pedestrians at the corner to the tram-side street. ▪ It was tough to travel from No. 172 to the destination due to a slope (cross slope). ▪ No. 80 to 172 was flat and easy to travel. ▪ It was crowded around No. 172. It was hard to travel there because many people did not notice the wheelchair.
Route discussed in the WS	▪ The S-street was crowded, but the sidewalk was wide enough to travel smoothly. ▪ The cross slope was steep. ▪ It was crowded and I had to be careful passing pedestrians. ▪ Compared with the cross slope of the street from No. 14 to 85 (K-street), it was easier to travel because of a gentle slope.
Route	**Opinions of Group B (Scenario B)**
Shortest route	▪ I wanted to continue to travel the S-street after the Node 48. ▪ I prefer the route with a lower physical burden even if I have to take a detour. ▪ The shopping arcade was easy to travel but crowded with pedestrians, and I was anxious about a collision. ▪ I could travel the S-street at ease because it is properly paved. ▪ The sidewalk of the Node 48-47 felt narrow because of signboards set up along it.

Route with a low physical burden	▪ The route was complicated and tough to travel. ▪ There were many level differences of the street, resulting in a high physical burden. ▪ It was tough to get off and back between the driveway and sidewalk. ▪ The sidewalk was partly narrow and I felt a danger.
Sidewalk-only route	▪ There was no need to worry about colliding with a car. ▪ I felt a lower physical burden. ▪ Slopes were not much bother. The streets were flat.
Route discussed in the WS	▪ The shopping arcade was easy to travel but crowded. I was anxious about colliding with a child. ▪ Shimotori (S-street) was easy to travel, but the physical burden was high at the Node 12-5 upslope. ▪ The tile pavement of the G-street caused big vibrations. ▪ Bigger vibrations result in a higher physical burden.

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