Note

Examining aspects of automated driving by people with spinal cord injuries:

Taking-over of steering in acute situations

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Abstract
Technological developments are in progress to realize automated driving, and people with physical disabilities are anticipating such support. The commercialization of automated vehicles will form an ideal means of mobility for people with physical disabilities as it will permit them to move from door-to-door and improve their quality of life (QOL). When a fully-automated driving system is developed, the operation of vehicles will rely solely on this system. However, at this time, all drivers need to handle acute situations by controlling their vehicles by themselves. Is it possible for physically-impaired drivers to take appropriate actions in such situations? People with spinal cord injuries—who include those with lower-limb disabilities—have to steer and regulate their speed simultaneously by using only their upper-limbs. This makes their driving posture and behavior unstable, and they find it more difficult to handle acute situations than people without physical disabilities. A manual operation-device operates simultaneously with the accelerator and the brake pedal of a vehicle. Taking this device as an example, it is installed in a limited space around the driving seat after the car is purchased, and this causes the device to be located in a position that does not suit the driver. The device is not designed for drivers to steer their car according to their physical condition, but rather it is designed for people to adjust their posture to drive.

Keywords
automated driving, people with spinal cord injuries, driving, acute situations, steering methods

1. Introduction

The development of autonomous vehicles has a long history. At the New York World's Fair in the U.S.A., from 1939 to 1940, the General Motors Company announced the concept of autonomous vehicles for the first time in the world [Tsugawa, 2015]. In the 1960s, research on autonomous vehicles began in Europe, and they were developed to drive on dedicated roads in the 1980s. About 60 years have passed since then, and the present goal in Japan is to see autonomous vehicles driving on some parts of general roads and expressways by 2020.

Japanese automakers have been advancing technological developments at a rapid speed in order to realize fully-automated driving, and some safety systems, such as "Autonomous Emergency Braking" and a "Lane Departure Warning System," have already been put into practical use. People with physical disabilities have also eagerly waited for fully-automated vehicles. Once such vehicles are put on the market, people with disabilities will be able to move from door-to-door freely, and their QOL will improve. Thus, autonomous vehicles will be an ideal means of mobility.

Table 1 shows different levels of automated driving as defined by SAE International in 2014. Today, the levels defined by SAE International are more common than those of the National Highway Traffic Safety Administration. Much progress has been made in the development of the automation of driving systems. It reached Level 2 in 2019 and it is now on its way to Level 3. According to Level 3 in the table, drivers are able to leave all operations related to driving to the system under limited circumstances, however, drivers have to take certain actions (such as a taking-over from automated driving) in acute conditions. Can drivers with physical disabilities make appropriate reactions and responses in a case of taking-over from automated driving to manual driving?

Obtaining a driving license has become legal for physically impaired drivers with some conditions since 1960 in Japan. Today, it is possible for people with spinal cord injuries who have a disability either in their lower-limbs or in their trunk—the most common cases among the physically impaired—to obtain a license [National Rehabilitation Center for Persons with Disabilities, 1994]. When people with spinal cord injuries drive a car, they need to install a manual operation-device after purchasing the car, and the device enables them to control the accelerator and brake of their car by hand (Figure 1). However, they face various problems in using the device. Drivers who have paralysis of the fingers or wrist flexion find it difficult to drive their car smoothly when their car has a commercial, manual operation-device installed. This situation causes difficulty for the drivers in selecting the right speed and in keeping a stable driving posture when driving on curves. Takaki et al. [2004] and Endo [1993] indicate that drivers' disabilities in upper-and lower-limbs and/or their body-trunk cause instability in their driving postures. It also causes inconsistency in controlling steering and other operations related to the manual operation-device. Even if a manual operation-device is installed to personalize a car which has been designed and manufactured for

Table 1: Automated-driving levels as defined by SAE International

Category	Narrative definition	Driving-task fallback
Level 0	All performances at this level, including acceleration, steering, and control of the car, are conducted by the driver. Forward Collision Warning and other driver assistance systems are also included at this level.	Driver
Level 1	Cars at this level have a system which supports acceleration, steering or control of the vehicles (e.g. lane departure sensing, automatic correction, and adaptive distance control).	Driver
Level 2	Cars at this level have a system which supports all or more than one area of acceleration, steering, and control of the vehicle (e.g. lane departure sensing, automatic correction, and adaptive distance control). However, drivers have to monitor their driving situation. The levels 0 to 2 are called levels of driving support technology, and are not automated driving.	Driver
Level 3	Cars at this level have a system which supports all performances relating to driving under limited circumstances. However, drivers must take action by themselves in acute situations.	Driver
Level 4	Cars at this level have a system which supports all performances relating to driving under limited circumstances. Drivers do not need to drive as long as the same circumstances continue, and the system also has control in acute situations.	System
Level 5	Cars at this level have a system which supports all performances related to driving under all circumstances. No driver is required for driving.	System

Source: SAE International [2014]. Taxonomy and definitions for terms related to on-road motor vehicle automated driving systems. (Some parts have been altered by the author.)

Figure 1: A general type of manual operation-device (Floor-type)

the use of the physically unimpaired, physically impaired drivers cannot make instant reactions if their way of controlling steering does not meet the range of movements of their bodies. When drivers with a disability face a situation in which they have to steer and regulate speed simultaneously, the difficulty they face is more severe than for physically unimpaired people [Ikeda et al., 2010a].

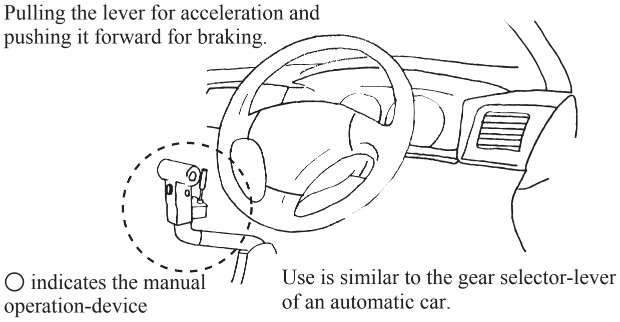
As described earlier, under today's conditions, drivers with disabilities install a driving-assist device to personalize a car which has been designed for driving by the physically unimpaired. In order to prevent repetition of the same situation in which the physically impaired adjust their ways of driving to vehicles, an automated-driving system should be designed by taking the driving characteristics of those with physical disabilities into consideration. The focus of this paper is on the problems that are likely to occur when a driver's control over a vehicle is shifted from automated driving to manual driving in acute situations, and discussion will be carried out concerning the driving mechanisms for persons with spinal cord injuries which have been demonstrated in earlier studies.

2. Driving performances of people with spinal cord injuries

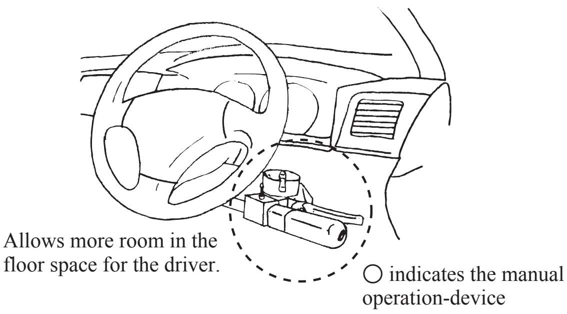
People with spinal cord injuries who have upper-limb or both-limb disabilities are legally approved to drive vehicles if a manual operation-device is installed in their vehicles (Figure 2). The device enables drivers to accelerate and decelerate their cars even if they cannot control the foot pedals for acceleration and braking. However, Ikeda et al. [2010b] point out that people with spinal cord injuries tend to have an unstable seated balance whey they are driving. When people without such disabilities drive a vehicle, they can support their body with their lower-limbs. This stabilizes their upper-body when driving on a curve because they need to use their upper-limbs only for controlling the vehicle, rather than for supporting their body like people with disabilities.

Fuji Auto, Inc. is the first company to develop a manual operation-device in Japan. The development of the device began with a traffic accident which left a taxi driver with a disability in both his legs. The taxi driver then developed a car that he could drive even with his condition [Fujimori, 2012]. Since then, manual operation-devices have been developed depending on types of disabilities. Typical manual operation-devices are the floor-type (Figure 2 (a)) and column-type (Figure 2 (b)), and the floor-type is more popular since it is easier and cheaper to install. Drivers operate the floor-type device by pulling the lever of the device backward for acceleration and pushing it forward for braking. The floor-type device is installed by fixing it to the floor of the car. The column-type has the body of the device set into the lower part of the steering column of the car, and this creates more room in the floor space for the driver. The operation method of the column-type is similar to operating a motorbike.

Drivers with spinal cord injuries are not capable of supporting their bodies with their lower-limbs, and their upper-limbs are used not only for controlling steering but also for control-



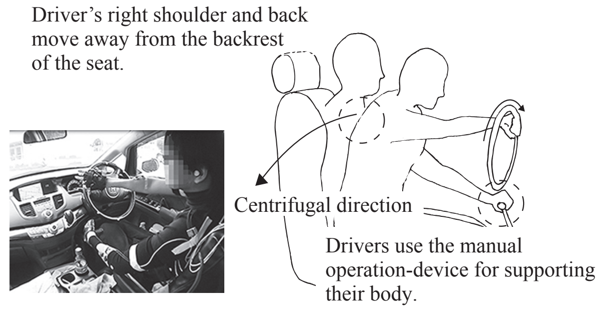
(a) Floor-type



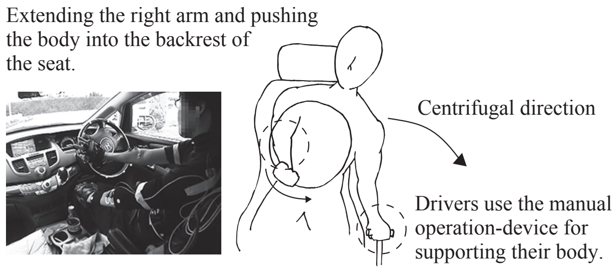
(b) Column-type

Figure 2: Examples of manual operation-devices used by drivers with spinal cord injuries

Note: Drivers have to control steering, acceleration, and braking by using only their upper-limbs.



(a) Making a left turn



(b) Making a right turn

Figure 3: Examples of driving postures of drivers with spinal cord injuries while making turns

ling speed when using the manual operation-device installed in their car [Iwasaki, 1992]. For these reasons, their upper-body falls forward when they push the lever of the floor-type device, and when they rotate steering to their left on a curve turning to the left, the back of their body (top of their shoulders) moves away from the backrest of the driver's seat [Hirose et al., 2015] (Figure 3 (a)). Unlike drivers without a disability, drivers with spinal cord injuries cannot use their upper-body by resting their back on the seat. Grandjean [1988] explains that operating pedals requires a high backrest since the action needs to produce great pressure. Thus, the role of the backrest in a car is important. When drivers with spinal cord injuries are turning their car to the right, they can support their upper-body by stretching their upper-limbs and making their body cling to the backrest of the driver's seat. However, they cannot control steering smoothly (Figure 3 (b)).

As described above, there are differences in steering methods between drivers with spinal cord disabilities and those without, and thus, they support their bodies differently when their driving postures become unbalanced. Dols et al. [1996] and Kember [1992] point out that the controlling procedures and design of vehicles do not supplement what is needed for such drivers fully. Taking a manual operation-device as an example, drivers have no choice but to install it after purchasing the vehicle in the limited space around the driving seat. Cars are not designed to fit to the conditions and operation methods of drivers, but are designed so that people adjust themselves to the cars. Such problems would not have occurred if consideration had been given not only to people without disabilities but also to the disabled at the car design stage.

3. Relationship between taking-over from automated to manual driving and driving by people with spinal cord injuries

The law and other problems have to be overcome for fully-autonomous vehicles to prevail in reality, however, steady progress is being made in order to fulfill the expectations of society. Since the appearance of fully-automated driving has become more likely, studies have been conducted by simulating autonomous vehicles in acute situations (though the subjects of the studies have been people without disabilities). For instance, Blanco et al. [2015] suggest that, in a case of taking-over from automated to manual driving, the timing of the take-over has a great impact on the actions taken by the drivers. Merat et al. [2014] also point out the instability of driving performance by drivers just after a take-over from automated to manual driving. Russell et al. [2016] conducted an experiment in which drivers take over control from automated to manual driving and then change lanes while driving. This experiment demonstrated that even people without disabilities had difficulty with actions in situations where speed was accelerated and steering reaction became more sensitive [Hayashi, 2018].

A questionnaire survey was conducted by the authors previously among 102 people with spinal cord injuries and 115 people without disabilities to find out the frequencies of problem occurrence while driving on curves. In a question asking about the frequency of problems in driving as the body slides or moves under the influence of centrifugal force, 59.0 % of the

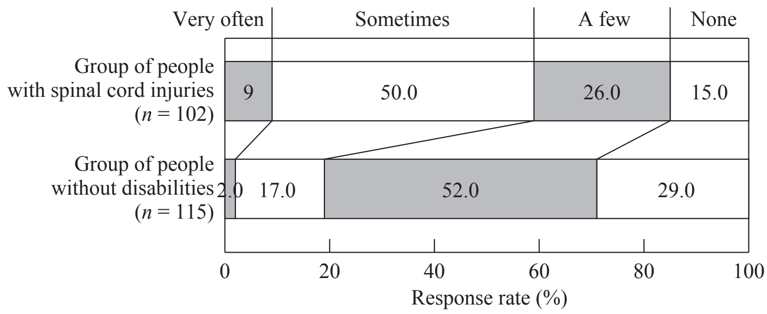


Figure 4: Frequency of problem occurrence caused by the impact of centrifugal force while driving

people with spinal cord injuries answered that problems occur “very often” or “sometimes.” For the same question, only 19.0 % of the people without disabilities answered “very often” or “sometimes” (Figure 4). People with spinal cord injuries have to keep the balance of the trunk of their body with their upper-body. This makes them vulnerable to centrifugal force, and hence, they find it more difficult to hold their driving posture compared to people without disabilities ($\chi^2 = 36.61$, $p < 0.01$).

Another questionnaire survey conducted previously by the authors concerned four traffic conditions for making right and left turns (i.e. two driving on curves and two on right-angle turns). The subjects of the survey were 55 people with spinal cord injuries and 96 people without disabilities. Curves and right-angle turns are considered conditions affecting driver performance. Left-curve conditions marked the most significant difficulty among the four conditions: 38.2 % for the group with spinal cord injuries and 10.4 % for the group without disabilities ($\chi^2 = 16.52$, $p < 0.01$) (Figure 5). The ratios were especially high for conditions on a left-curve and during a right-turn. This indicates that drivers have difficulty in driving when their body-trunk moves sideways under the influence of centrifugal force for both of these situations. In a question asked about coming closer to the edge of and departure from a driving lane, the situation not only for a left-curve but also for a right-curve ($\chi2 = 320.52$, $p < 0.01$) and left-turn ($\chi^2 = 850.76$, $p < 0.01$) were found significant in difficulty (Figure 6). Under traffic conditions in which drivers are affected by a certain

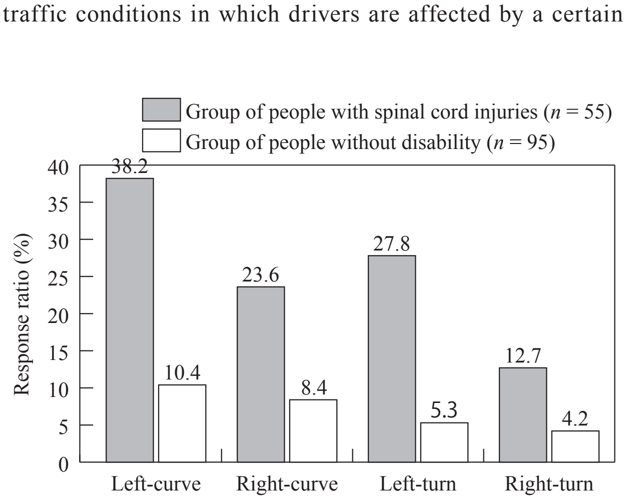


Figure 5: Road conditions with difficulty of driving

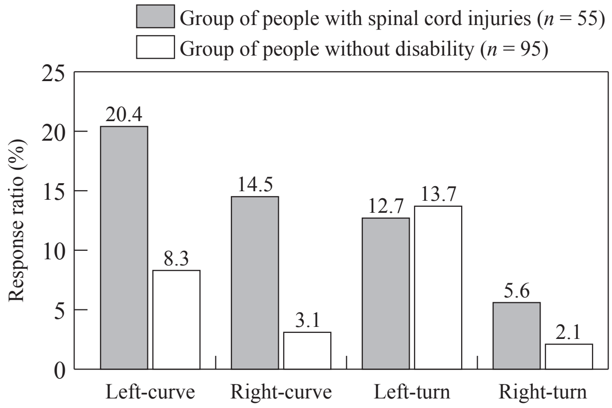


Figure 6: Coming closer to the edge of and departure from a driving lane under different road conditions

degree of centrifugal force, cars driven by people with spinal cord injuries tend to move to the edge of driving lanes.

Drivers who are driving automated vehicles of the Level 3 type, as shown in Table 1, are released from actual driving and they need only to monitor it. Kawamoto [2017] points out the difficulty of controlling an airplane appropriately in a case of a take-over from automated to manual piloting. According to Kawamoto, in such a situation the pilots have to face a sudden change to their mental condition from a relaxed situation when the plane is flying using auto-pilot to a tense situation when the control has been switched to manual flying. Drivers are usually conscious of where the pedals are in a car, such as the accelerator pedal being next to the brake pedal. However, the pedals are located depending on the driver’s condition in the case of automated driving, and thus, there are more possibilities of the driver making mistakes in controlling pedals. Gold et al. [2016] suggest that a certain amount of time is required for drivers to regain their usual sense of driving after a take-over from automated to manual driving. Ito et al. [2015] suggest the necessary time is three to five seconds, while a German auto-maker suggests five to ten seconds [Tomioka, 2018]. Japan’s Ministry of Land, Infrastructure, Transport and Tourism [2016] concludes that drivers should allow a minimum of four seconds for this kind of take-over.

A quick take-over of control when driving, such as a take-over from automated to manual driving, provokes an unstable driving performance. Thus, it is more difficult for drivers with spinal cord injuries to have stable driving conditions compared to people without disabilities.

The authors have engaged in research and development in order to improve the driving environments of people with spinal cord injuries, and this was begun by investigating the road as well as drivers' conditions when problems occur while driving. One of the R&D aspects is a comprehensive evaluation of driving behavior, posture, and the muscle tension of drivers when they are driving on curves on urban expressways [Ikeda et al., 2007a; 2011]. The results of the study reveal that the sense of ease and comfort felt by drivers does not equate to how safely they are driving. A questionnaire survey conducted as a part of the R&D also reveals that drivers found a certain rotation-direction difficult when steering a car, and they also found difficulties in driving and holding their upper-body in an appropriate posture [Ikeda et al., 2007b]. Another problem found in an experiment on driving on roads with sharper-angled curves was that when the driving speed increased, the control of steering was kept constant regardless of the road shape [Ikeda et al., 2008]. Thus, when a car is driven at a certain speed, and its driver returns the car to a direct route after finishing making a turn, the actions taken for maintaining driving posture greatly influence the driver's driving procedure.

Moreover, people with brain or spinal cord injuries may experience their lower-limbs moving or opening to right- and left-directions unconsciously while they are driving. This is caused by a symptom called spasticity. In a question asked about drivers' experience of their lower-limbs touching the manual operation-device, steering wheel, or foot pedals while driving (43 respondents), 27.9 % of the drivers with spinal cord injuries answered that they touched the device while driving, with 16.3 % for the steering wheel, and for 34.9 % foot pedals (Figure 7). When drivers with spinal cord injuries are taken into consideration for the development of automated driving, it should be noted that the symptoms caused by spasticity could influence their driving performances at an unconscious level.

Automated vehicles meeting the standard of Level 3 in Table 1 have a system which controls acceleration, steering, and braking, and drivers are completely free from driving the

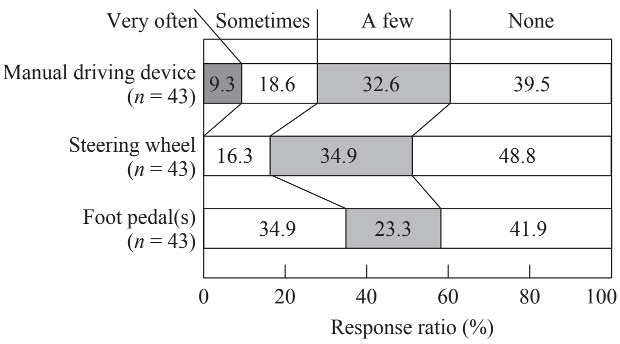


Figure 7: Experience of touching some devices in a car with lower-limb(s) because of spasticity

vehicles. However, as described above, drivers with spinal cord injuries are likely to find it difficult to take action in acute situations when their cars move sideways and their posture is unstable. Even people without disabilities find it difficult to handle acute situations, and thus, we should expect that people with spinal cord injuries would find it much more difficult to deal with. When drivers find no problem in driving autonomous vehicles, there is no need to worry. However, if some kind of trouble occurs and the drivers of autonomous vehicles are expected to handle the situation by themselves, then those vehicles must have been developed on the basis of the characteristics of drivers with disabilities. Without this, the vehicles cannot be considered really automated vehicles.

4. Conclusion

It is obvious that necessary devices should be installed before putting cars on the market. People with spinal cord injuries are capable of driving a car, however, their driving performance is often less stable than that of driving by people without disabilities. A human interface needs to be developed for people with spinal cord injuries, so that steering environments for driving will be presented based on the driving functions of people with disabilities. Now is the time to give consideration to such issues because systems for automated driving have not yet been completely developed, and in this way we will not make the same mistakes as in the past.

When people are driving a car and the car's system has support functions for driving at Level 1 and 2 in Table 1, then the automation of driving will be very helpful for people. However, the system for cars above Level 3 provides automation, not support, and drivers will act as an observer. In the case of acute situations, or when the control of a vehicle is shifted from automated to manual driving without any choice for the driver, then drivers need to take various actions to deal with their situation. Drivers with spinal cord injuries are forced to face more difficulties than people without disabilities in handling such situations, since the maintenance of driving posture greatly influences a person's driving procedure.

A car is not merely a tool for mobility for people with spinal cord injuries. It can be a part of their body, and it gives them an opportunity to be on the same level as people without disabilities. Makers of welfare devices have produced devices to support the driving of people with disabilities, but unfortunately they are of a type that is installed after purchase. Installing something to an already completed product could ruin the original concept of the product.

This paper has considered people with upper- and lower-limb disabilities, however, the discussion should not be limited only to people with such disabilities but also consider elderly people, whose lower-limbs will weaken. People with lower-limb disabilities and elderly people, whose physical ability in the lower-limbs has deteriorated, share similar problems. One of those problems is the retention capability of the body when the position of the upper-body becomes unstable. For this reason too, study is required on developing systems for automated driving which can provide safe driving conditions for drivers even in the case of the take-over from automated to manual driving in acute situations.

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