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# Driving Skills Assessment in Individuals with Spinal Cord Injuries: A Pilot Test of ADRIS 3.0 Simulator

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*Abstract*— **Driving can improve the independence of people living with a disability and positively impact their lives. However, driving is a complex activity that can be affected by many factors. Among them, people who want to return to driving after a spinal cord injury, have often to re-learn driving with hand-adapted devices. Thus, a driving simulator allows one to train driving skills in a safe environment and can help to assess fitness to drive by creating challenging and realistic situations the users must promptly face. This work presents an adapted version of ADRIS 3.0 (Accessible DRIving Simulator), specifically tailored to people with spinal cord injuries. The simulator has a three-monitor visualization mode, and it is usable with different realistic driving controllers, thanks to a custom-made peripheral device. The new version of the simulator was tested with eleven individuals with different levels of spinal cord injury. Following the experimenter's instructions, participants were asked to drive in a test scenario before and after a 30-minute training on four different maps of increased difficulty. Results demonstrated that the simulator is well-tolerated in terms of simulation-related symptoms and effort levels. Performance data revealed an improvement between the beginning and end of each session. Altogether, these preliminary results support the idea that the new version of ADRIS could improve the training and evaluation of the driving skills of individuals with spinal cord injuries.**

## I. Introduction

Spinal cord injury (SCI) is a highly disabling condition caused by damage to the spine, resulting in motor and sensory issues below the injured site [1], [2] . In most cases, the spinal cord damage is irreversible, but specific treatments can prevent the onset of secondary injuries that may worsen the individual's condition [1]. SCI is an event that completely changes individuals' lives and makes them face a series of physical, emotional, and social challenges. Reintegration into society is indeed a key aspect to enhance the quality of life and it is strictly related to the independence level of the SCI person [3]. Silver et al. [4] defined the major obstacles encountered by people with SCI in the first year after the injury: self-reported barriers were related to mobility, equipment and transportation, with mobility identified as a key factor in receiving the care needed immediately after the injury. In this context, independence in mobility is a key factor to enhance quality of life, and this can be achieved through driving.

Driving is indeed associated with engagement in daily and social activities, autonomy, improved self-confidence, and occupational possibilities [5]. Little is known about perceptions of drivers with SCI on driving and return to driving, Mtetwa et al. [5] examined the post-injury driving experiences of some post-SCI drivers. All the participants remarked that before returning to drive they felt 'isolated', 'stuck' and 'stranded'; this was also due to often inadequate or expensive public transportation. On the other hand, several participants expressed different benefits of driving a car. Importantly, they reported a lack of appropriate recommendations and professional guidelines when returning to driving. Another significant aspect is the emotional support needed to prepare psychologically people who want to return to driving as they may need to overcome possible symptoms of post-traumatic stress disorder [5]. For all these reasons, driving rehabilitation may lead to the construction of a new self-identity following a SCI [3].

Against this background, driving simulators can be fundamental tools for the assessment and rehabilitation of motor and cognitive skills following an injury. Indeed, simulators allow the user to drive in a safe, realistic environment, or one in which the difficulties faced are the same as those observed during a street driving session [6]. An important advantage of simulators is the possibility to control the environment in which the driving takes place, in addition to the possibility to analyze performance variables that could not be captured in a road driving situation [7]–[9]. The use of simulators can be extended to various areas and applications, especially road safety monitoring and rehabilitative uses. In rehabilitation, the focus is on people who, due to accidents or disabling diseases, have motor disabilities that do not allow

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them the same driving and movement opportunities as subjects without disabilities. When a person with motor or sensory impairments desires to return to driving, occupational therapists can recommend adaptive driving devices to compensate for these limitations [3]. However, learning to drive with these new assistive technologies can increase the difficulty of the driving task, mental workload and risks on the road, so it could be beneficial to begin driving in a controlled and safe environment [10].

### A. Driving Simulators

Nowadays, there are many available simulators, but they still have some limitations, especially in the context of assessment and training for people living with a disability. Top-tier driving simulators come with a price in the range of one hundred thousand dollars, demand significant space, and are consequently impractical for clinical settings [6], [11]. Also, many of them replicate a real car and include a fixed seat, but this is a barrier for people with motor disabilities that does not allow them independent access to the simulator platform [12]. Finally, many systems do not provide fully realistic, immersive environments, while others simply cannot personalize scenarios or monitor driving performances due to limited outcome measures: these systems cannot thus be used for training or an objective evaluation of the fitness to drive of people with disability.

This work aims to expand the capabilities of the Accessible DRIving Simulator developed in our lab [8], [9] (ADRIS 2.0) and already tested in its previous and simplest version with people with multiple sclerosis [13], to make it more realistic and immersive for testing the driving skills of people with spinal cord injury. The updated version of the simulator - ADRIS 3.0 - was tested on individuals with spinal cord injuries, asking them to drive in different scenarios following a predefined protocol. Specific attention was given to the level of physical and mental fatigue resulting from the simulation and the possible onset of symptoms related to motion sickness, which often characterizes the use of virtual reality-based simulators. The resulting data from the tests serve as a starting point to design training protocols and define metrics to assess driving abilities in people with spinal cord injuries objectively.

## II. Material and Methods

The simulator can be divided into a hardware and a software system. The hardware part includes a PC, driving controllers and a visualization device (Fig. 1), while the software architecture is based on Unreal Engine 4.

### A. The updated simulator: ADRIS 3.0 Hardware

This work focused on changing the hardware system to add realistic driving controllers, and to implement a triple-screen mode to augment the immersivity of the simulator. Also, the possibility of being wheelchair accessible without the need for the subject to move on special seats is one of the most important features of the new version. These three points were specific requests made by medical doctors, physicians, and physiotherapists of the Spinal Cord Unit of the Santa Corona hospital in Pietra Ligure, SV, Italy where the tests were run.

The previous version of ADRIS had a gaming steering wheel (Logitech G920 Driving Force Wheel), which has been replaced by realistic controllers that must interact with the PC, allowing computer-peripheral communication. This choice was made because the gaming steering wheel is smaller than a real one; it has buttons instead of manual commands, that are normally present in car steering wheels (e.g., directional lights). The installed steering also includes commands for directional lights, night lights, and wipers. All these commands are mapped as switches and therefore have only two states: ON and OFF (Figure 1, top panel). To codify the information related to the steering wheel rotations, we coupled it with a 5-multiturn potentiometer (Bourns 3548S-1AA-103A, 10kΩ of resistance and an independent linearity of 25%). This configuration allows the steering wheel to make 1.5 turns in clockwise from the central position and 1.5 turns counterclockwise. A mechanical block was added as a safety measure to avoid the sensor breaking if more than 1.5 turns were attempted. This addition was also useful to create a behavior more like the one of a real car.

In addition to the steering wheel, we created adaptive driving devices like the ones used by people with lower-limb deficits. They normally use hand-controlled devices to accelerate and brake, instead of the pedal controls. We recreated a joystick similar to one of Paravan solutions [14]. Specifically, drivers can use a one-axis joystick that allows them to accelerate or brake through the movements of a lever; this device works in combination with the car's steering wheel. Alternatively, they can use another version that has two axes: the first is for gas and brake, while the second replaces the steering function. We used a 2-axis commercial joystick (RS PRO 2-Axis Joystick controller), so it can be used in combination with the steering wheel (as a 1-axis joystick) or

Figure 1. Hardware components of ADRIS 3.0. Real car steering wheel, automatic transmission and adapted brake/accelerator (top), and the three-screen configuration for improving the driving experience (bottom).

alone (Fig. 1): in the former case, one of the two axes can be mechanically blocked by a plate. This joystick has ± 20 degrees of stick movement from the center position and has springs that make it return to the center. The stick inclination in the two directions is codified by two potentiometers (5k Ω resistance and an independent linearity of 2%). Finally, we added a third piece of hardware to simulate the automatic gear shift composed of four buttons (park P, reverse R, neutral N, drive D) which can be pushed to select the corresponding gear (Fig. 1).

An an Arduino Micro microcontroller was used to manage all the above-mentioned hardware and implement a correct connection and communication with the PC, leveraging the Human Interface Device (HID) standard. This allowed having a built-in USB communication and using the controllers as a standard peripheral. To manage all the physical connections between the Arduino board and the driving controllers, three shields have been realized: two of them are implemented to receive signals from the steering wheel's cables and transfer them through flat-8 conductors, and the third instead allows the connection between Arduino and all the other devices (e.g., joystick).

Lastly, a triple-screen visualization modality was implemented (Fig. 1, bottom) allowing to expansion the view of the driver. This way, when the driver reaches a crossroad, he/she can view what is happening not only in front but also laterally in the scene by looking at the lateral monitors. The visualization devices include three monitors (LG-32MN500M) full HD 1920x1080 pixel, 31.5-inch display, 16:9 aspect ratio, Response Time 5ms, 5M dynamic contrast and 250 cd/m2 brightness, 67-83 Hz horizontal refresh rate, 60-74 Hz vertical refresh rate. These features satisfy optimal technical requirements [11]. The physical configuration of the three monitors reflects the positions of the virtual cameras placed in the virtual environment to avoid any distortion. A Field Of View of 50° was selected that allows the user to be seated at 75 cm far from the screens, which is on average the real distance of a driving seat (see Fig.2).

## *B. The updated simulator: ADRIS 3.0 - Software*

The software architecture of ADRIS 3.0 was not substantially changed from the previous versions [8], [9], [13]. The simulator is based on Unreal Engine 4 (Epic Games, Cary, NC, USA). It includes a graphic interface, easy to use by different users, artificial intelligence (AI) managing the simulations, and realistic sounds, and it allows for the creation of customized scenarios. With ADRIS, it is possible to control several variables like traffic intensity, weather, and light conditions. Moreover, unexpected events can be generated, either static or dynamic (e.g., a vehicle not respecting the red light in the opposite direction, a pedestrian suddenly crossing the road, or objects on the street [8], [9], [13]). Concerning the previous versions, the software was adapted to allow communication from the new driving controllers, collected through the Arduino Micro board and mapped to the simulated car. Also, the user car has now three cameras attached to its body, to allow the three-screen visualization mode.

From the simulation some useful indexes for monitoring and evaluating user performance are saved: car trajectory, speed, driven distance, simulation duration, number of collisions, lane crossings, running red lights, and stops.

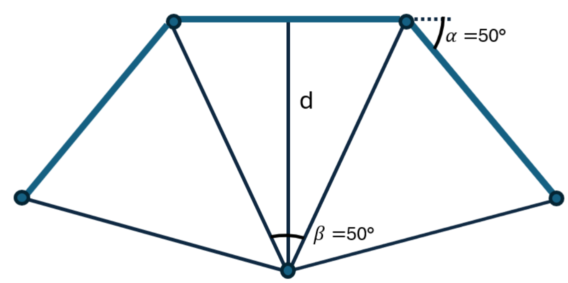


Figure 2. Monitor positioning (in blue) in the three-screen modality with a field of view of 50°.

*Table 1*. Demographic information of spinal cord injured subjects. ASIA stands for American Spinal Cord injury association impairment scale, score A=complete injury no motor and sensory function below lesion, B=incomplete injury retention of sensory function only, C=incomplete injury retention of motor function and muscle grade less than 3, D=incomplete injury retention of motor function and muscle grade greater than 3. Injury level C=cervical, T=thoracic, D=dorsal, L=lumbar.

| *Subject ID* | *Injury Level* | *ASIA score* | *Age (yo)* | *Sex* | *Years with driving license* | *Driving frequency before the lesion* | *Frequency of videogame use* | *Glasses user* | *Car Sickness* |
|---|---|---|---|---|---|---|---|---|---|
| SC01 | D5 | A | 18 | F | No driving license | NA | Never | Yes | No |
| SC02 | D10 | A | 70 | F | >10 | daily use | Never | No | No |
| SC03 | L3 | C | 67 | M | >10 | daily use | Never | No | No |
| SC04 | D6 | A | 25 | M | No driving license | NA | Once a month | No | No |
| SC05 | L3 | C | 76 | M | >10 | Weekly use | Never | Yes | No |
| SC06 | D5 | A | 18 | M | > 2 | daily use | Daily | No | No |
| SC07 | D11 | A | 49 | M | >10 | daily use | Never | No | No |
| SC08 | C6 | C | 60 | M | >10 | daily use | Never | Yes | No |
| SC09 | T3 | A | 75 | M | >10 | daily use | Never | Yes | No |
| SC10 | C6 | C | 62 | M | >10 | daily use | Never | No | No |
| SC11 | D12 | D | 44 | M | >10 | daily use | Never | No | No |

## B. *Subjects*

The study was conducted at the Spinal Cord Unit, Santa Corona Hospital of Pietra Ligure (Savona, Italy). We recruited eleven subjects with spinal cord injuries (age: 51 ± 22 years old, 2 females). See Table I for more detailed information. The study was approved by the Institutional Review Board (code CE DIBRIS protocol - N. 2022/52 approved on 22/09/2022) and it conformed to the ethical standards of the 1964 Declaration of Helsinki. Each subject provided written informed consent to participate in the study and to publish individual data.

## C. *Experimental Set-Up and Protocol*

Before the experiment, subjects were asked to complete a questionnaire about motion sickness, experience with video games, and whether they wore glasses or contact lenses. The experimental session lasted about 40 minutes and it was divided into successive phases where the subject drove in the scenarios (see Fig. 3) characterized by different events (i.e., hazardous situations). In particular:

• Free Drive: five minutes of familiarization in a scenario free of traffic, events, and obstacles; the session can be repeated if the subject needs additional time to learn how to use the simulator.

• Scenario 00 (Test): pre-training phase in which the subject is required to follow a guide vehicle for two minutes in the absence of traffic and with good weather conditions.

• Scenario 01: the subject is required to follow the experimenter's guidelines to drive in a low-traffic environment with good weather conditions and an object on the road as the main event.

• Scenario 03: the subject follows the experimenter's guidelines to drive in a light traffic environment on a sunny day, with a stationary vehicle on the roadway as the main event.

• Scenario 05: the subject is required to follow the experimenter's indications to drive in a medium-traffic environment at sunset, while driving a pedestrian crosses the road immediately after a curve as the main event.

• Scenario 07: following the experimenter's indications, the subject drives in a heavy traffic scenario at night, with rocks falling on the road as the main event.

• Scenario 00 (Test): post-training phase equivalent to that carried out at the beginning of the experiment.

Subjects could take breaks between the different scenarios to prevent the onset of fatigue.

At the end of the session, three questionnaires were administered to evaluate the experience with the simulator.

- Simulator Sickness Questionnaire (SSQ) [15] to measure any symptoms experienced during the simulation due to the discrepancy between the visual and vestibular systems, as a movement in virtual reality corresponds to the stance of the subject. Subjects need to answer various questions on a scale from 0 to 3.
- NASA Task Load Index (TLX) [16] to measure mental and physical demands and effort. It is composed of six indexes to which the subjects need to express a score from 1 (low effort) to 20 (high effort).
- Igroup Presence Questionnaire (IPQ) [17] to evaluate the sense of presence in the virtual environment and experienced realism. Score from 1 (disagree) to 7 (totally agree).

## D. *Simulator Data Analysis*

The performance analysis is focused on the mean driving speed (MDS) and the number of collisions/infractions (nCI) divided into car collisions, ignored red lights and ignored stop signs. After verifying the normality assumption, paired t-test for continuous parameter (MDS) and Wilcoxon signed-rank test for discrete parameters (nCI) statistical analyses were conducted in Matlab (MathWorks, Natick, MA, USA) to assess performance differences between the pre- and post-training phases.

# III. Results

## A. *Driving performance analysis*

In figure 4 top panel are shown the average speeds among the SCI population for each scenario. Driving mean speed increased after the training (Fig 4, top panel). Indeed at the beginning, the MDS was 21.30±2.30 km/h and in the post-training scenario it was significantly higher 23.72±2.23 ($p=0.009$), suggesting an increase in safety and familiarity in the driving simulation by the user, which is crucial from a rehabilitation and training perspective. In the training phase, the mean speed was dependent on the difficulty of the driven scenario. Lower MDS indicate complex scenarios, with smaller roads and higher traffic volumes.

Comparing collisions and infractions committed in pre-training and post-training, an improvement between the first and last driving can be inferred (Fig.4, bottom panel). The number of collisions and infractions decreased between the initial test Pre-TR and the final test Post-TR (respectively from 0.4±0.3 to 0.3±0.2 not significant, and from 0.9±0.3 to 0.2±0.1 $p=0.0312$). Similarly to the MDS, collisions and infractions in the training phase, seem to be closely dependent on the scenario, and thus a function of the different traffic levels and unexpected events that characterize each scenario. No influence of age or ASIA levels was noticeable from this preliminary analysis.

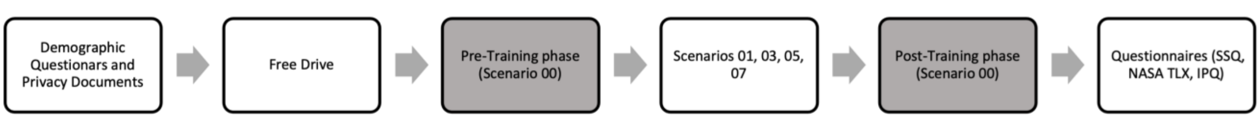


Figure 3. Experimental Protocol. The session was divided in different phases, before and after the use of the driving simulator questionnaires were administered to the participant. Then, the driving phase consisted in an initial familiarization with ADRIS 3.0 (Free Drive), followed by a pre-training scenario, four training scenarios and a final post-training scenario identical to the pre-training one. During the different scenarios the driving scene, light and traffic volumes changed accordingly to the difficulty of the scenario. After the driving, participants filled out three questionnaires. SSQ, NASA TLX and IPQ.

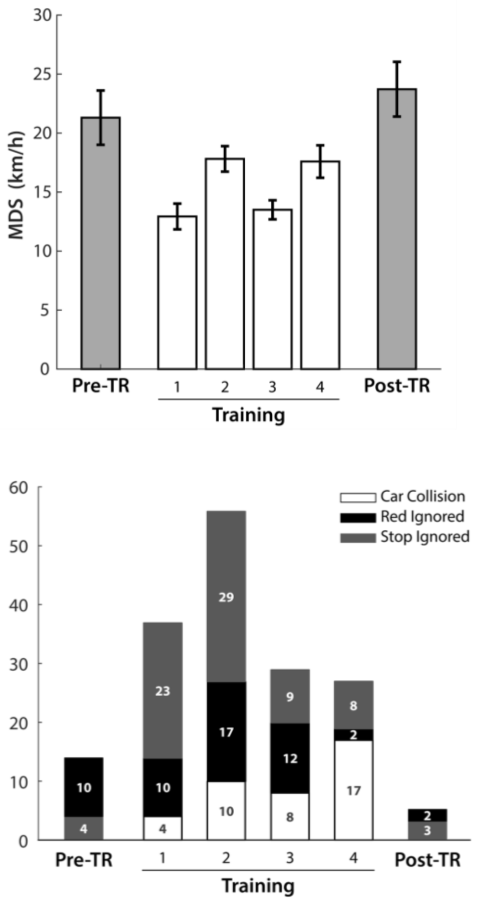


Figure 4. Mean and standard error of the mean velocity over all SCI subjects (top); sum of infractions and collisions for each scenario for the SCI population (bottom).

## B. Driving Experience

The results of the questionnaires are reported in Fig. 5. From the SSQ, people reported no signs of general discomfort (median 0, range: [0-1]) and very low symptoms related to motion sickness (nausea: median 0, range [0-1]; dizziness: median 0, range [0-2]; belching: median 0, range [0-2]; sweating: median 0, range [0-3]; increased salivation: median 0, range [0-1]; headache: median 0, range [0-2]; head pressure median 0, range [0-2]; dizziness: median 0, range [0-1]) and also fatigue (median 0, range [0-3]). In conclusion, an excellent tolerance of the simulator and the virtual environment with which the subject interfaces in the test sessions can be highlighted through the analysis of the symptoms.

Results from the NASA TLX (Fig. 5, middle panel) questionnaire revealed a low level of frustration (median 3, range [1-10]) and physical demand (median 6, range [1-20]), Of notice, one of the participants had considerable difficulty in moving the left arm; therefore, he reported high values of physical, temporal, and mental demand, as well as low performance. Overall, participants reported moderate temporal demand (median 10, range [1-20]), high mental demand (median 12, range [10-20]), and high level of effort (median 14, range [1-20]). In general, the indices obtained show moderate efforts under the different domains, and this may be due to the motor disabilities the subjects have.

The results of the IPQ (Fig. 5, right panel) were divided into four subgroups: involvement, sense of presence, presence in the virtual world, and realism. The analysis of the obtained data reports moderate involvement (mean 4.25, standard deviation ± 1.12), moderate sense of presence (4.6 ± 1.58), high presence in the virtual world (4.73 ± 2.37), and rather low realism (3.86 ± 1.09). These values are good responses for the quality of virtual reality and involvement in that environment due to the immersive system realized by the three monitors and the very realistic sound system. The low realism is an indicator of running the test sessions in a hospital environment and not in conditions that may approach those of real driving.

# IV. Conclusion

The positive results obtained in this study proved that the hardware modifications made on ADRIS 3.0, make it an accessible and highly customizable driving simulator for people with SCI. Future development will include expanding the library of adaptive driving tools to connect to ADRIS 3.0, and the development of an appropriate force feedback for the steering wheel and vehicle dynamic, to further increase the realism of the simulator. Additionally, to better quantify driving performance additional parameters like steering time can be added to the ones currently used. This preliminary study can be a starting point for the design of training protocols, which consider the needs of people with spinal cord injuries. Also, the present version of ADRIS might help in the definition of performance metrics to objectively assess the driving abilities of SCI drivers, ultimately improving their independence and autonomous living.

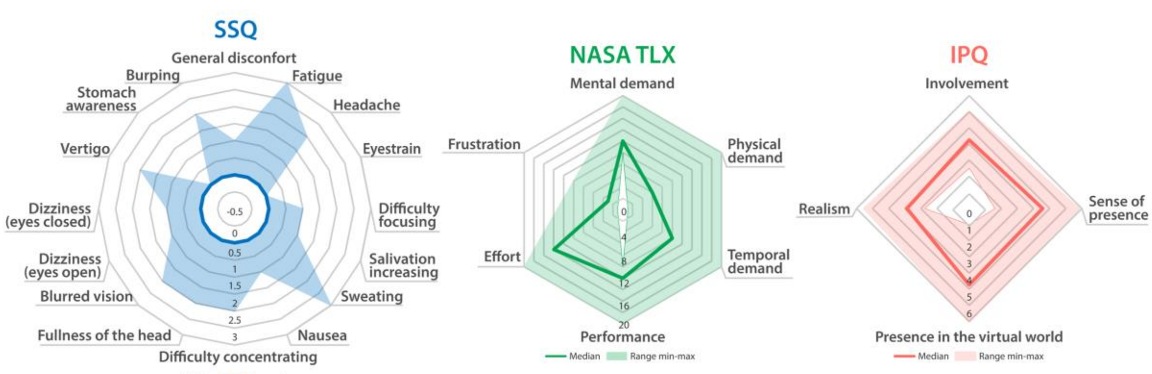


Figure 5. Simulation Sickness Questionnaire (left), NASA Task Load Index (middle), Igroup Presence Questionnaire (right) subjects with SCI. Solid lines represent the median and shaded area represent maximum and minimum values of the SCI population.

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