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A novel low-cost solution for driving assessment in individuals with and without disabilities

Jakob Rodseth [a], Edward P. Washabaugh [a, c], Ali Al Haddad [a], Paula Kartje [a], Denise G. Tate [a], Chandramouli Krishnan [a, b, c, *]

[a] Department of Physical Medicine and Rehabilitation, University of Michigan Medical School, Ann Arbor, MI, USA
[b] School of Kinesiology, University of Michigan, Ann Arbor, MI, USA
[c] Department of Biomedical Engineering, University of Michigan, Ann Arbor, MI, USA

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ABSTRACT

Brake reaction time is a key component to studying driving performance and evaluating fitness to drive. Although commercial simulators can measure brake reaction time, their cost remains a major barrier to clinical access. Therefore, we developed open-source software written in C-sharp (C#) for measuring driving related reaction times, which includes a subject-controlled vehicle with straight-line dynamics and several testing scenarios. The software measures both simple and cognitive load based reaction times and can use any human interface device compliant steering wheel and pedals. Measures from the software were validated against a commercial simulator and tested for reproducibility. Further, experiments were performed using hand controls in both able-bodied and spinal cord injured patients to determine clinical feasibility for disabled populations. The software demonstrated high validity when measuring brake reaction times, showed excellent test-retest reliability, and was sensitive enough to determine significant brake reaction time differences between able-bodied and spinal cord injured subjects. These results indicate that the proposed simulator is a simple and feasible low-cost solution to perform brake reaction time tests and evaluate fitness to drive.

1. Introduction

The safe operation of a motor vehicle in response to an unexpected dangerous situation (e.g., a pedestrian suddenly crossing the road) generally depends on how quickly a driver can react and bring their vehicle to a complete stop by applying the brake. Therefore, a subject's ability to quickly react to a situation (i.e., reaction time) is critical for optimal driving performance (Anstey et al., 2012; Horberry and Inwood, 2010; Paxion et al., 2015; Ba et al., 2016; Smith et al., 2015). Accordingly, clinicians and researchers often evaluate driving reaction time when performing a medical assessment to determine fitness to drive (Liebensteiner et al., 2016; Hofmann et al., 2016a; Schwienbacher et al., 2015; Jordan et al., 2015). Reaction time is a derivative of several sensorimotor capabilities—mainly an individual's cognitive, neuromuscular, and visual capacity. Although the impact of these capabilities themselves on driving performance is not clearly understood (Greve et al., 2015), tests that impart a load on a driver's cognitive, motor, and-or visual domains can alter brake reaction time. Therefore, they are useful in assessing one's driving ability (Anstey et al., 2012; Fitch et al., 2014; Marciano and Yeshurun, 2015; Innes et al., 2009).

A comprehensive on-road driving test is the gold standard for assessing fitness to drive (Bedard et al., 2010; Weaver and Bédard, 2012). However, on-road assessment is not always feasible, and testing a range of situations can be difficult and potentially dangerous to examine on the road. Driving simulators provide a safe, convenient, and configurable testing environment to perform these tests (Bedard et al., 2010; Reimer et al., 2006; Johnson et al., 2011; Kraft et al., 2010). This is especially useful when considering the need to evaluate driving skills of populations with special needs such as the elderly, those with physical disabilities, and young adults learning how to drive for the first time. Furthermore, driving simulators can be configured to include specific testing requirements necessary for comprehensive evaluation. For example, an evaluator can add adaptive hand controls for

* Corresponding author. Neuromuscular & Rehabilitation Robotics Laboratory (NeuRRo Lab), Department of Physical Medicine and Rehabilitation, University of Michigan, 325 E Eisenhower Parkway (Suite 3013), Ann Arbor, MI, 48108, USA.
E-mail address: mouli@umich.edu (C. Krishnan).

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Abbreviations

HID	Human Interface Device
2D	Two-dimensional
3D	Three-dimensional
GUI	Graphical user interface
RPM	Rotations per minute
SCI	Spinal Cord Injury
ANOVA	Analysis of variance

individuals with neuromuscular disability, or alter road conditions to simulate driving in the rain or at night (Bedard et al., 2010). Driving simulators can also accurately and efficiently measure performance, which allows for the standardization and reproduction of test procedures and results. For these reasons, reaction time assessments in studies concerning driving ability are generally measured using commercial driving simulators (Greve et al., 2015).

Commercial, high-end driving simulators are accurate, feature rich, and offer a breadth of possibilities for training and evaluating drivers. However, the cost of high-end simulators usually runs in the one hundred thousand dollar range with less complex simulators still priced at tens of thousands of dollars (Weinberg and Harsham, 2009). Furthermore, full size simulators that include features such as projections, car cabins, and virtual reality environments require large amounts of space to operate and are expensive to maintain. As an alternative to large, high-end simulators, desktop simulators are also available. Research shows these types of simulators are adequate in producing data that accurately reflects on-road and commercial simulator results (Nef et al., 2013; Park et al., 2005; Dahmani et al., 2012; Gibbons et al., 2014). However, cost is still prohibitive to the accessibility of these simulators because proprietary equipment, such as specific monitors, computers, and custom input devices are often required for the simulator to function correctly. These restrictions make their use in certain environments, such as a physician's clinic, infeasible (Weinberg and Harsham, 2009). Therefore, there is a critical need for a low-cost, clinically feasible simulator as an alternative to existing commercial simulators.

In this manuscript, we describe the design and implementation of a two-dimensional (2D) driving simulation software for reaction time assessments. The software is free and open source and compatible with computers running Microsoft Windows operating systems, making it highly accessible and adaptable, especially to those with programming knowledge. The program offers comprehensive reaction time measurement, testing scenarios, and cognitive load settings to obtain a complete picture of a subject's driving performance. Human Interface Device (HID) compliant input devices, such as a steering wheel and pedals, are the preferred input methods as they offer high data resolution and give subjects a more realistic sense of driving. For ease of use, keyboard input is also supported as a method for user control. We estimate the minimum cost to optimally interface with the simulator program is about $250 (based on the cost of commercial gaming grade steering wheel and pedals). We also validated our simulation software against an existing commercial desktop simulation software and tested the repeatability of the reaction time measurements obtained from the low-cost simulator. Finally, we also tested the clinical utility of our system by comparing the driving reaction time data from able-bodied individuals to those with spinal cord injury (SCI). The results from these experiments indicate that our simulation software provides both reliable and valid reaction time data, making it feasible for a clinical environment.

2. Methods

This study was performed in two phases: (1) Development phase – a 2D driving simulation software (i.e., in-house) to assess reaction time was developed and implemented with commercially available steering wheels, pedals, and adaptive hand controls, and (2) Validation phase – the program was validated against a commercial 3D simulator and test-retest reliability was established by comparing results across two different days. We also validated the clinical utility of the system by comparing the driving reaction time data from able-bodied individuals to those with spinal cord injury (paraplegia). A summary of the in-house and commercial simulators used in the validation can be seen in Fig. 1.

2.1. Simulation software development

The simulation software is a Windows form application written in C# that can utilize up to two USB compliant HID (gamepad, steering wheel, pedals). Through the graphical user interface (GUI), an examiner can select a test to administer to the subject. The subject interacts with a simple, top-down view of a car on a straight stretch of road (Fig. 2a). The simulation is handled by a fixed time step, variable render loop to ensure consistent simulation across different hardware configurations. The loop polls an input device for its state, processes any changes to the state, passes these updates to the physics engine, updates the simulation state, and finally updates the screen to reflect the new simulation state. The simulator was designed to provide a realistic driving sensation by simulating simple, straight-line vehicle dynamics. It supports several different testing scenarios to facilitate the construction of a complete picture of a subject's driving reaction time performance. The simulator measures reaction time events and stores the data in a summary file and per-trial raw data dump. The executable and source code of the simulation software can be downloaded from our lab's website (http://neurro-lab.engin.umich.edu/downloads).

2.1.1. User interface - user display

Because the program simulates straight-line automotive physics, the user display consists of a straight stretch of road rendered to visualize the simulation state. A speedometer and tachometer are placed on the right and left sides of the road respectively to give feedback to the subject, while the subject's vehicle is located on the road (Fig. 2a). The car can move left and right, speed up, slow down, and move in reverse in accordance with the subject's input. However, visually, the car does not move vertically on the screen. Instead, velocity is emulated by the movement of the center lane lines relative to the velocity of the subject's car. During reaction time events, event entities, such as a stop sign or a deer, behave similarly to the center lane lines; they appear at the top of the screen and move towards the bottom relative to the velocity of the subject's car. Entities that have velocity, such as a lead car located in front of the subject's car, match the subject's velocity until a reaction time event, at which point deceleration is rendered as motion towards or away from the subject's car relative to the difference in velocity between the two entities.

2.1.2. User interface - examiner control

The examiner may modify the simulator scenarios, controls, and internal variables to accommodate their experimental requirements and goals. Using the system's *input control panel* (Fig. 2b), the user can select the input devices (e.g., steering wheel, pedal, joystick) and individual axes (or buttons located on the input devices) of the input devices that control the game object (i.e., the car). The input control is designed in such a way that the user can automatically assign a control (e.g., acceleration, brake, turn, etc.) to