THESIS

DETERMINANTS OF DRIVING PERFORMANCE FOLLOWING STROKE

Submitted by

Aviva Katherine Pollet

Department of Health and Exercise Science

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Master's Committee:

Advisor: Neha Lodha

Kaigang Li
Arlene A. Schmid

ABSTRACT

DETERMINANTS OF DRIVING PERFORMCE FOLLOWING STROKE

Overall introduction: Individuals with stroke experience motor and cognitive deficits both of which can impact driving performance. Using two separate studies, we evaluated the influence of motor and cognitive factors on driving performance in stroke survivors. In the first study, we evaluated how driving impairments in stroke survivors is influenced by the use of either the paretic or non-paretic leg for pedal control. *Methods 1:* Twenty-two individuals with chronic stroke were recruited in two groups depending on their lower-limb choice for pedal control 1) paretic leg drivers, individuals using their paretic leg to control the car pedals (*N* = 11, 68.4 ± 7.8 years) and 2) non-paretic leg drivers, individuals using their non-paretic leg to control the car pedals (*N* = 11, 61.1 ± 13.7 years). Both groups performed a car following task in a driving simulator. The task required participants to follow a lead car by controlling the gas pedal accurately and respond to brake lights by pressing the brake pedal as fast as possible. We quantified gas pedal error using root mean square error (RMSE). We measured brake response time as the time from the onset of the brake lights of the lead car to the application of the brake pedal. We also dissociated the brake response time into pre-motor and motor response times. We used the Driving Habits Questionnaire (DHQ) to measure self-reported on-road driving behavior. Additionally, using surface electromyography (EMG), we analyzed neuromuscular activation using burst duration and amplitude, and coordination using overlap and coactivation of the tibialis anterior (TA) and medial gastrocnemius (MG)

during the braking portion of the car following task. *Results 1:* The paretic leg drivers showed greater gas pedal RMSE than the non-paretic leg drivers ($p \leq 0.01$). The paretic leg drivers had a slower brake response time than the non-paretic leg drivers ($p < 0.05$). Premotor response time was not different between the two groups ($p = 0.71$), however, the paretic leg drivers had a significantly slower motor response time relative to the non-paretic leg drivers ($p < 0.05$). The paretic leg drivers had lower DHQ scores than the non-paretic leg drivers ($p \leq 0.01$). DHQ and brake response time were negatively correlated ($r = -0.42$, $p \leq 0.05$). Additionally, paretic leg drivers showed longer TA EMG burst duration ($p < 0.05$) and more TA-MG overlap ($p < 0.05$). TA EMG burst duration was positively correlated to brake response time ($r = 0.51$, $p < 0.05$) and motor response time ($r = 0.61$, $p < 0.05$). TA-MG overlap was positively correlated to brake response time ($r = 0.76$, $p = 0.001$).

<u>In the second study,</u> we evaluated how cognitive load influenced driving impairments in stroke survivors. *Methods 2:* Ten individuals with chronic stroke participated in the current study ($N = 10$, 65.6 ± 14.9 years). The participants performed simulated driving without (single-task) and with (dual-task) a cognitive load. The single-task driving required participants to drive along a rural road and brake as quickly as possible when an unexpected hazard, such as wildlife crossing into the driving lane, was encountered. The dual-task driving required participants to drive in the same driving scenario while performing a secondary cognitive task. The cognitive task involved mental arithmetic to induce higher cognitive load while driving. Specifically, participants were asked to subtract 4 and add 3 to a random number and do so repeatedly until the end of the driving task. We measured lane departures as the number of times the edge of the participant's vehicle

left the designated driving lane. We measured speed compliance as the percent of total time the individual was within +/- 5 MPH of the speed limit between events. Additionally, we measured brake response time as the time from the appearance of the hazard stimulus to the application of the brake pedal. *Results 2:* Individuals with stroke show more lane departures throughout the entire drive during dual-task driving than single-task driving ($p < 0.05$). Additionally, individuals with stroke show worse speed compliance during dual-task driving than single-task driving ($p < 0.05$). There was no difference in brake response time between the single-task and dual-task driving ($p = 0.18$). *Overall conclusion:* Driving performance in stroke survivors is influenced by limb selection for pedal control and cognitive load. The current studies demonstrate the need to assess and train motor and cognitive deficits that contribute to driving performance in individuals with stroke. Motor deficits in pedal control and brake response time contribute to unsafe driving in individuals with stroke. Cognitive deficits in lane departures and speed compliance in driving with cognitive load also contribute to unsafe driving in individuals with stroke. To address these deficits, stroke driving rehabilitation programs should focus on driving leg and cognitive environment of driving.

ACKNOWLEDGEMENTS

I would like to thank Dr. Neha Lodha and Dr. Prakruti Patel for their endless support and mentorship throughout this process. Without them, none of this would have been possible. Additionally, I would like to thank each member of the Movement Neuroscience and Rehabilitation Lab, together we are “one big brain” and that brain can do amazing things. In particular I would like to thank my “sister in science” Laura Taylor. It was not only your mentorship but your friendship that kept me sane in the months leading up to this thesis.

Thank you to my family for putting up with my rambling about research for the past two years, and to my mother for genuinely being interested. I cannot thank you all enough for everything you have done and continue to do to support me. I am lucky to have five beams of light illuminating my path, wherever it may go.

Thank you to my friends who pretended to understand what I was doing the last two years. Most importantly, thank you to those of you who were a captive practice audience for countless scientific presentations.

DEDICATION

For Bop, who gave me so much, most importantly my love of learning. I know you would have been proud.

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CHAPTER 1 - INTRODUCTION

Driving is a fundamental part of everyday life that facilitates independence and safe mobility (Aufman et al., 2013). Therefore, returning to safe driving is a common rehabilitation goal following stroke. It has been established that compared to healthy controls, individuals with stroke experience deficits in the cognitive and motor functions required for safe driving (Hird et al., 2018, Lodha et al., 2021). To date, driving performance in individuals with stroke is typically evaluated in comparison to healthy control individuals. However, stroke is a heterogeneous disease such that symptoms and deficits may vary significantly among individuals. Therefore, the approach of grouping all individuals with stroke together fails to identify distinct deficits that may be related with the specific clinical characteristics of the stroke. To address the gap in the driving literature in the stroke population, the following two studies presented in this thesis will evaluate motor and cognitive determinants of safe driving in individuals with stroke. Specifically, in Study 1, we evaluate the motor component of driving by examining how paretic or non-paretic limb selection for pedal control, influences diving performance. In study 2, we examine the cognitive component of driving by determining the influence of cognitive load induced by a dual-task on driving performance. The current studies will improve our understanding of how driving performance in stoke survivors is influenced by limb selection and cognitive load and will facilitate development of individualized rehabilitation protocols that will promote returning to safe driving and help maintain independence following stroke.

CHAPTER 2 - MANUSCRIPT 1

Driving Performance is Influenced by Whether the Paretic or Non-paretic Leg is Used for Car Pedal Control Following Stroke

2.1 Introduction

Driving after a stroke is a key aspect of maintaining occupational, financial, social, and medical independence (Aufman et al., 2013). Stroke impacts the cognitive and motor functions critical for safe driving (Hird et al., 2018, Lodha et al., 2021). Compared with healthy controls, adults with stroke demonstrate longer brake reaction time, exaggerated steering wheel movement, and poor speed compliance and lane positioning (Blane et al., 2017, Hird et al., 2014, Lodha et al., 2021). Importantly, most of the evidence to date regarding poor driving performance following stroke emanates from studies that evaluated all individuals with stroke together, without distinguishing whether the paretic or the non-paretic leg was used for pedal control. Applying a “one-size-fits-all” approach of driving evaluation limits our ability to understand the unique driving deficits that may be associated with the heterogeneous nature of stroke. Investigating the influence of leg selected for pedal control on driving performance will identify specific driving deficits related to the driving leg and ultimately promote and prolong safe driving in individuals with stroke.

Typically, driving relies heavily on the use of the right leg for manipulating the gas and brake pedals, known as pedal control. However, stroke typically causes unilateral motor deficits that may affect one side of the body to a greater extent than the other. Of the individuals who return to driving following stroke, approximately 35 % experience right-hemispheric stroke with left side paresis, while 59 % have left-hemispheric stroke with right side paresis (Almosallam et al., 2021, Aufman et al., 2013). Individuals with left side paresis who return to driving often continue to use their right, non-paretic leg to control the pedals. However, individuals with right side paresis have a choice in driving leg. Depending on the severity of motor impairment, some individuals may re-learn pedal control with their non-paretic left leg with a car modification, while others may continue to drive with their paretic right leg. Given that long-term impairments after stroke are common, driving with the paretic leg may impact the ability to drive in a safe manner (Bohannon, 1991, Canning et al., 1999, Ouellette et al., 2004, Wist et al., 2016). Thus, understanding whether driving outcomes in the stroke population differ when driving with the paretic versus the non-paretic leg can help in developing targeted driving rehabilitation strategies after stroke.

Recent driving studies suggest that driving performance may differ based on the laterality of stroke. During on-road driving, driving performance in the right-hemispheric stroke was influenced by divided attention whereas driving performance in the left-hemispheric stroke was affected by visual scanning, speed of processing, and executive dysfunction (Devos et al., 2014). Additionally, in simulated driving, individuals with right-hemispheric stroke had more turn signal errors, errors in using the seatbelt, speed maintenance, road following, and center line crossings. Individuals with left-hemispheric stroke demonstrated longer brake reaction time (Park, 2015). However, it is not clear whether stroke laterality related differences in driving performance in these studies were influenced by the paretic versus non-paretic limb selection for driving.

The aim of the current study is to determine how pedal control differs when using the paretic leg versus the non-paretic leg for driving in individuals with stroke. Pedal control was measured with gas pedal accuracy and brake response time in a simulated driving environment. We hypothesized that pedal control with the paretic leg will be associated with diminished driving performance compared to pedal control with the non-paretic leg. Specifically, gas pedal error will be greater and brake response time will be longer in individuals driving with the paretic leg. Understanding the unique driving motor impairments of the paretic leg drivers and non-paretic leg drivers will ultimately facilitate a more personalized approach to driving rehabilitation following stroke.

2. 2 Materials and Methods

Experimental design

This between subjects experiment consisted of a single session lasting about two hours that included cognitive, motor, and driving assessments. Individuals started by completed a global cognitive screening assessment and processing speed assessments. Immediately following the cognitive assessments, participants completed motor impairment and strength assessments. Finally, participants completed a driving task involving following a lead car and responding to brake lights by releasing the gas and applying the brake as quickly as possible.

Twenty-two individuals with stroke participated in the current study. Participant characteristics are presented in **Table 2.3.1.** Inclusion criteria for the individuals with stroke were self-reported: (1) diagnosed with a unilateral cerebrovascular accident prior to testing, (2) currently driving using the lower extremity or had been driving prior to stroke, (3) a minimum active range of motion of 15 degrees of ankle dorsiflexion and 5 degrees plantarflexion against gravity, (4) the ability to understand and follow a three-step command (e.g., “Take this piece of paper in your right hand. Fold it in half. Put the paper on the floor.”), (5) vision or corrected vision of 20/20 with no visual neglect. Exclusion criteria were (1) presence of any other neurological or musculoskeletal disorder, (2) pain or injury affecting limb movements, (3) spatial neglect, vision, and hearing impairments, (4) psychiatric illness (such as clinical depression or anxiety) or untreated sleep disorder, and (5) history of simulator sickness. The self-reported scores on these impairments were used to screen the participants. Individuals with stroke were classified into either the paretic leg drivers or non-paretic leg drivers group based on stroke laterality and the leg they chose to drive with. All individuals who drove with the paretic leg used the right leg for controlling the pedals. The individuals who drove with the non-paretic leg self-selected to use either the right or left leg to control the pedals. The non-paretic-left leg drivers were provided with pedal modifications to drive in the simulator to match their own car. All individuals read and signed an informed consent approved by the University of Florida’s Institutional Review Board, prior to participation.

2.2.1 Cognitive assessments

<u>Montreal Cognitive Assessment:</u> We used the Montreal cognitive assessment (MoCA), a widely used cognitive screening measure to determine global cognitive status. MoCA is scored out of 30, lower scores indicate impaired cognitive status (Nasreddine et al., 2005).

<u>Useful Field of View:</u> To measure the cognitive processing speed in divided and selective attention tasks, we used the Useful Field of View (UFOV) test, a strong predictor of safe driving in stroke survivors (Clay et al., 2005, Marshall et al., 2007, Mazer et al., 2001). *Experimental set up:* Participants sat in an upright position in front of a 17inch monitor

(Sync Master™ 275t+, Samsung Electronics America, NJ, USA) placed at eye level, 0.60 m away. The monitor displayed the UFOV assessment.

Data measurement: Performance threshold for the cognitive processing speed was identified by reducing the duration of stimulus presentation progressively as the participant successfully completed previous trials. Divided attention task: Divided attention measured the ability to attend to central and peripheral stimuli simultaneously. We instructed the participants to correctly identify a central stimulus (a car or a truck) and simultaneously identify the location of a peripheral stimulus (a car). A longer time to accurately respond to both stimuli indicated poorer divided attention. Selective attention task: Selective attention measured the ability to direct attentional processes to two specific stimuli while voluntarily suppressing attention to distractors. A longer time to accurately respond indicated poorer selective attention. This task was identical to the divided attention task except that the peripheral target was embedded within several distractors.

2.2.1 Motor assessments

Fugl Meyer Assessment: We assessed the severity of lower extremity motor impairment using the lower extremity subsection of the Fugl-Meyer Assessment (FMA). FMA is scored out of 34, lower scores indicate a higher degree of motor impairment.

Strength: The maximal isometric force was quantified during ankle dorsiflexion and plantarflexion measured in the seated position with a force transducer. Participants increased force and maintained the maximal force for 3 seconds. The participants completed three to five maximum voluntary contraction (MVC) trials or until two MVC trials were within 5 % of each other. A 60 second rest was provided between successive trials.

The order of the dorsiflexion and plantarflexion MVC was randomized between participants.

Data measurement: The isometric forces exerted were measured with a force transducer (model 41BN, Honeywell, Morristown, NJ) that was located perpendicular to the force direction on the customized foot device. The ankle force signals were band-pass filtered from 0.03 to 20 Hz, sampled at 1000 Hz with a NI-DAQ card (model USB6210, National Instruments), and stored on a personal computer for analysis. We quantified dorsiflexion and plantarflexion strength as the highest value of the MVC force across all the trials.

2.2.3 Driving assessments

<u>Driving Habits Questionnaire:</u> Self-reported driving behavior was determined by the Driving Habits Questionnaire (DHQ), which assessed current driving status, driving exposure, space, avoidance, and citations (Owsley et al., 1999). We combined the above factors for a self-reported driving score with a maximum score of 15 and a higher score indicating increased involvement in on-road driving.

<u>Simulated driving assessment:</u> Participants performed a driving task involving following a lead car in the driving simulator. *Experimental set-up:* Participants sat in a car seat with a gas pedal, brake pedal, and steering wheel. The simulated driving task was performed with the self-selected driving leg, either the paretic or non-paretic leg. The foot rested on a customized gas pedal. The simulated driving environment was displayed on a 32-in. computer monitor (Sync Master 320MP-2, Samsung Electronics America, resolution: 1920×1080, refresh rate: 60p Hz).

Task: Participants were instructed to accurately track a lead car (visual target) by controlling the gas pedal with ankle movements. At random times, the brake lights of the lead car lit up. Participants reacted to the brake lights as quickly as possible by moving their foot from the gas pedal to the brake pedal and applying a controlled force on the brake pedal. The participants performed a total of 13 trials. The first three trials were familiarization trials and excluded from the analysis. The direction and position of the car was maintained by custom software and therefore did not require the use of a steering wheel. Each trial lasted 20 seconds with a rest period of 60 seconds between consecutive trials to minimize fatigue. After each trial, participants were provided visual feedback on the gas pedal error and the brake response time.

Pedal position measurement and analysis: The force from the brake pedal was measured using a force transducer (Model LAU200, 100 IbF capacity, FUTEK Advanced Sensor Technology, Irvine, CA). The position from the gas pedal was measured using the CSR Elite Pedals (Fanatec, Endor AG, Germany). The tibialis anterior activity was measured using wireless surface electromyography electrodes (Delsys Trigno; Delsys, Boston, MA). Gas pedal error: We determined gas pedal error using root mean square error (RMSE) that quantified the distance between the visual target and the participant's gas pedal position. *Brake response time*: We measured brake response time as the time between the onset of the brake lights of the lead car to the application of force on the brake pedal with a threshold of 2 N. We dissociated the brake response time into premotor response time and motor response time. Premotor response time quantifies the cognitive processing time for brake response and was measured as the time between the onset of brake lights and the activation of the tibialis anterior. The motor response time quantifies the movement execution time and was measured as the time from the activation of the tibialis anterior to the brake pedal application. *Neuromuscular Activation and*

<u>Coordination:</u> The activity of the tibialis anterior (TA) and medial gastrocnemius (MG) were measured using wireless surface electromyography electrodes (Delsys Tringo™, Delsys, Boston, MA). Data was sampled at 1 kHz and amplified (1000x) with NI-DAQ board (Model USB6218, National Instruments, Austin, TX, USA) and stored on a personal computer. The interference (raw) EMG was rectified and smoothed with a fourth-order Butterworth digital filter (filtfilt) with a cutoff frequency of 6 Hz. We used the filter EMG signal to identify the peak EMG amplitude, onset (15% of peak EMG), and offset (15% of peak EMG) of each muscle's EMG burst. We examined muscle activity by quantifying the following variables: *EMG burst duration* – the time between EMG onset and offset, and *EMG burst amplitude* – the peak EMG activity within the EMG burst, normalized to the EMG recorded during the MVC trials. In addition, we examined agonist-antagonist (TA-MG) coordination by quantifying the following variables: *Overlap* – equation 1 and *Peak Coactivation* – equation 2.

$$TA - MGOverlap\ (\%) = \frac{OffsetTAEMGburst - OnsetMGEMGburst\ (ms)}{OffsetMGEMGburst - OnsetTAEMGburs\ \ (ms)}\ X\ 100 \qquad (1)$$

$$TA - MGPeakCoactivation\ (\%) = \frac{2\ x\ MGamplitude}{TAamplitude + MGamplitude}\ X\ 100 \qquad (2)$$

2.2.4 Statistical analysis

To determine the influence of the leg used for pedal control on driving performance in stroke survivors, we compared gas pedal error (RMSE), brake response time, premotor response time, and motor response time between the paretic leg drivers and the non-paretic leg drivers. We performed a Shapiro-Wilk test to determine normal distribution of our data. All variables that were normally distributed (brake response time and premotor response time) were analyzed with independent samples *t*-tests. All variables that were not normally distributed (gas pedal error and motor response time) were analyzed with

Mann-Whitney U tests. Additionally, we performed Mann-Whitney U tests on MoCA, cognitive processing time in divided and selective attention tasks, and DHQ. Since four of our participants in the non-paretic leg drivers group used the left leg to drive, we did a secondary analysis to compare the driving performance of the non-paretic-left leg drivers to the non-paretic-right leg drivers. This analysis was conducted for the non-paretic leg drivers only because all paretic leg drivers used the right leg for pedal control. Additionally, to examine the relationship between self-reported driving behavior and pedal control, we conducted Pearson's correlation between DHQ, and gas pedal error as well as brake response time. To determine differences in the neural activation and coordination of the TA and MG muscles, we conducted independent samples *t* tests to compare paretic leg drivers to non-paretic leg drivers on EMG amplitude, duration, overlap, and peak coactivation of the TA and MG. To determine whether differences in the neuromuscular activation of the muscles were related to differences in braking performance, we used Pearson correlations. The alpha level was set at $p < 0.05$. Effect size was reported with Cohen's d for all normally distributed variables and r for all not normally distributed variables. All analyses were performed using IBM SPSS 26.0 (IBM, Armonk, NY).

2.3. Results

2.3.1 Participant characteristics

Table 2.3.1 shows the demographics and clinical characteristics of the stroke groups. The two groups did not differ in age, ($|t_{20}| = - 1.31$, $p = 0.10$). The two groups did not differ on the cognitive performance as indicated by MoCA score, *(*$U = 52.5$, $z = - 0.53$, $p = 0.30$), cognitive processing speed on the divided attention task ($U = 11.0$, $z = - 0.14$, $p = 0.44$) and the selective attention task ($U = 43.0$, $z = - 0.85$, $p = 0.20$). Lastly, the two groups did not differ on the severity of motor impairments as measured by the Fugl Meyer lower extremity assessment, (U = 41.0, z = - 1.30, p = 0.10), and maximum voluntary contraction of dorsiflexion ($|t_{19}|$ = 0.18, p = 0.43) and plantarflexion ($|t_{19}|$ = 0.31, p = 0.38).

Table 2.3.1: Participant characteristics. *MoCA – Montreal cognitive assessment; FMA-LE – Fugl-Meyer motor assessment for lower extremity; MVC – Maximum voluntary contraction*

	Non-Paretic Leg Drivers (*N*=11)	Paretic Leg Drivers (*N*=11)
Age (years)	61.1 ± 13.7	68.4 ± 7.8
Gender (Female)	3 (27%)	4 (36%)
Hemiparetic side (Left/Right), N	7/4	0/11
Time Since Stroke (years)	6.48 ± 4.0	3.8 ± 5.2
FMA-LE		
Motor (/34)	24.2 ± 7.3	27.0 ± 7.0
MVC force of Driving Leg (N)		
Plantarflexion	79.72 ± 15.45	73.30 ± 13.67
Dorsiflexion	172.35 ± 21.29	166.31 ± 26.29
MoCA (/30)	24.3 ± 4.7	23.7 ± 4.8
UFOV (ms)		
Divided Attention	111.0 ± 154.3	104.6 ± 150.7
Selective Attention	207.1 ± 145.2	241.0 ± 129.8

2.3.2 Driving performance

Gas Pedal Error: **Figure 2.3.1** shows the RMSE of the gas pedal. We found a significant difference between the two groups, (U = 32.0, z = - 1.87, p = 0.03, r = 1.17) on gas pedal error such that the individuals who drive with the paretic leg (16.0 ± 5.3°) demonstrated significantly greater gas pedal error than the individuals who drive with the non-paretic leg (11.3 ± 2.1°).

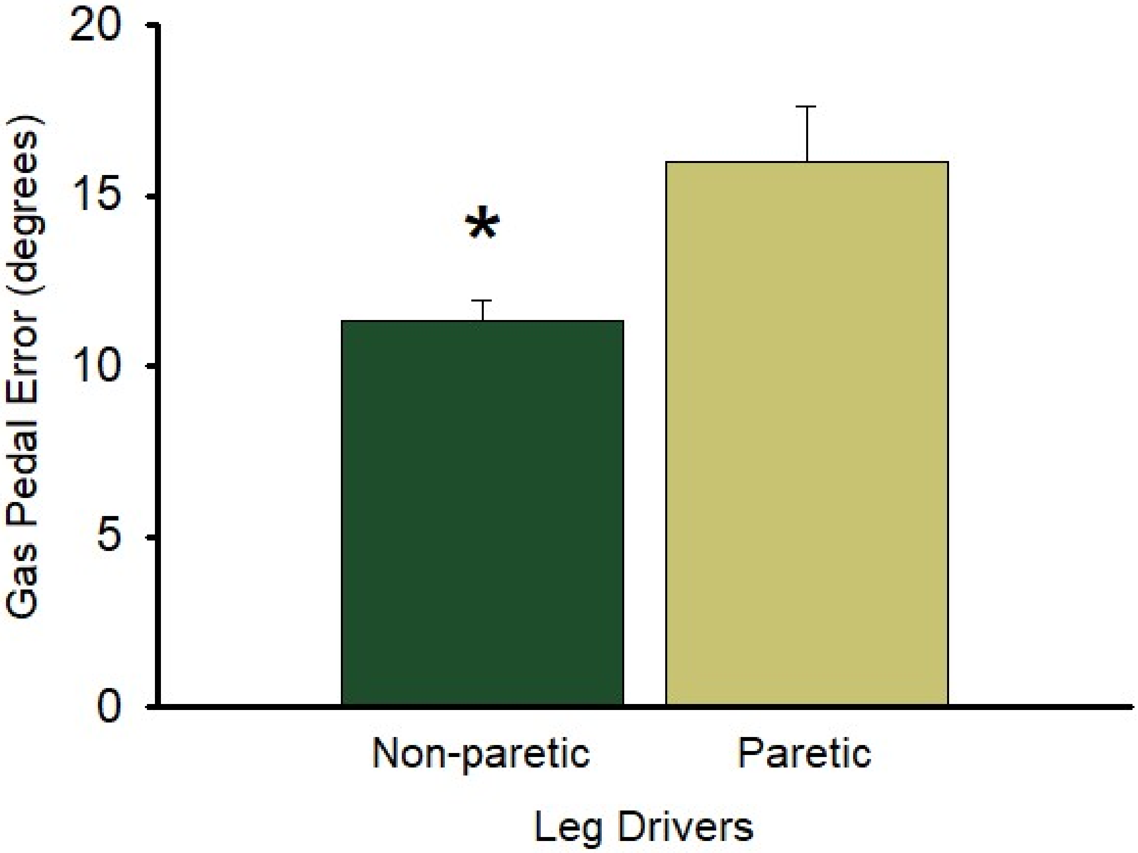

Figure 2.3.1 Gas pedal error during a car following task. The error bars represent standard error. The individuals who drive with the paretic leg show significantly more gas pedal error than the individuals who drive with the non-paretic leg. Significance is indicated by $*p < 0.05$.

Brake Response Time: **Figure 2.3.2** shows the brake response time for both groups. We found a significant difference in brake response time, ($|t_{20}| = -2.10$, $p = 0.02$, $d = 0.89$). The individuals who drive with the paretic leg (1002.6 ± 145.6 ms) demonstrated significantly longer brake response times than the individuals who drive with the non-paretic leg (872.6 ± 144.3 ms). **Figure 2.3.2** also shows the premotor and motor brake response times for both groups. The two groups did not differ on premotor response time, paretic leg drivers (500.60 ± 151.55 ms), non-paretic leg drivers (478.35 ± 123.38 ms) yet showed significantly different motor response times ($U = 20.0$, $z = -2.66$, $p < 0.01$, $r =$

1.10). The individuals who drive with the paretic leg (502.0 ± 114.0 ms) demonstrated a significantly longer motor response time than the individuals who drive with the non-paretic leg (394.3 ± 80.8 ms).

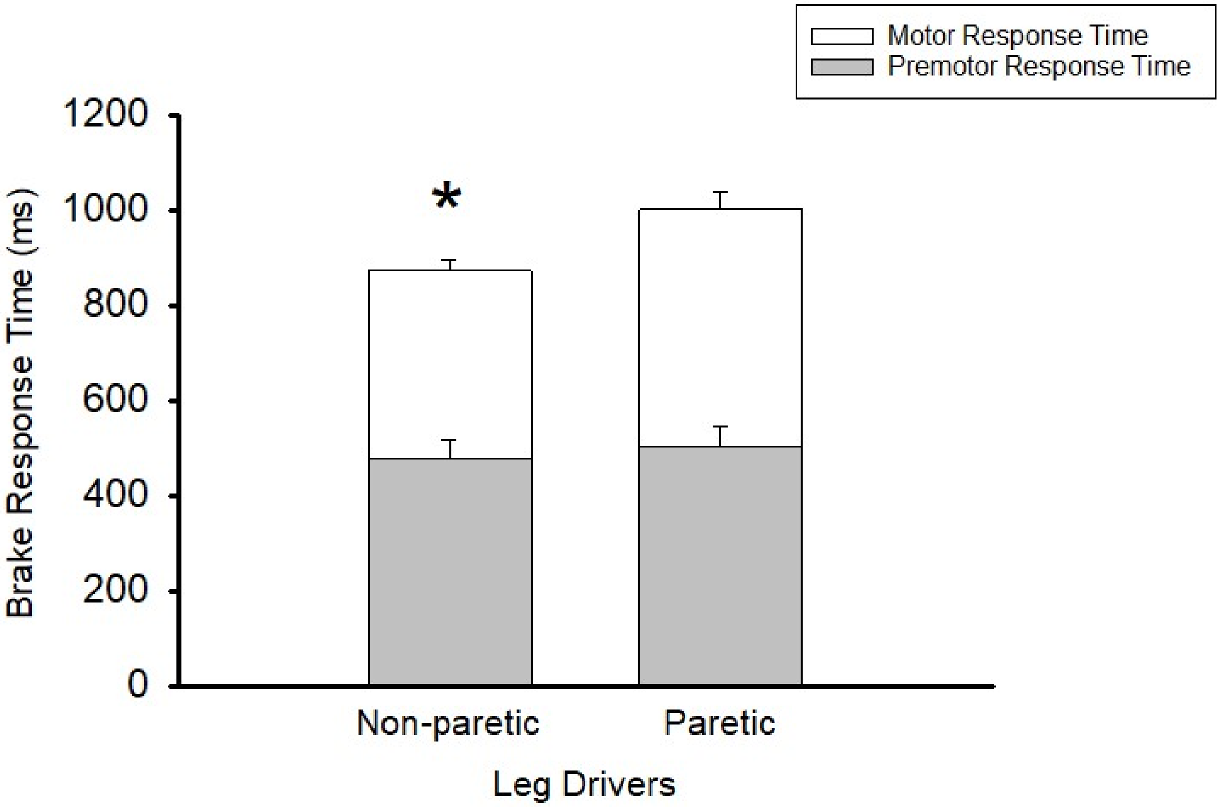

Figure 2.3.2 Brake response time during a car following task. Brake response time is dissociated into premotor and motor response times. The individuals who drive with the paretic leg show significantly slower motor response time and significantly slower brake response times than the individuals who drive with the non-paretic leg. Importantly, there is no difference in premotor response time between the two groups. *$p < 0.05$.

2.3.3 Driving behavior

Figure 2.3.3 shows the self-reported driving behavior of the two groups. The individuals who drive with the non-paretic leg (12.2 ± 2.7) demonstrated significantly higher scores on DHQ, ($|t_{20}| = 2.81$, $p = 0.01$, $d = 1.2$) than the individuals who drive with the paretic leg (6.1 ± 6.7). Additionally, we found a significant negative relationship between DHQ and brake response time ($r = -0.42$, $p \leq 0.05$) suggesting that brake response times was faster in individuals with better self-reported on-road driving behavior. We found no significant correlation between DHQ and gas pedal error.

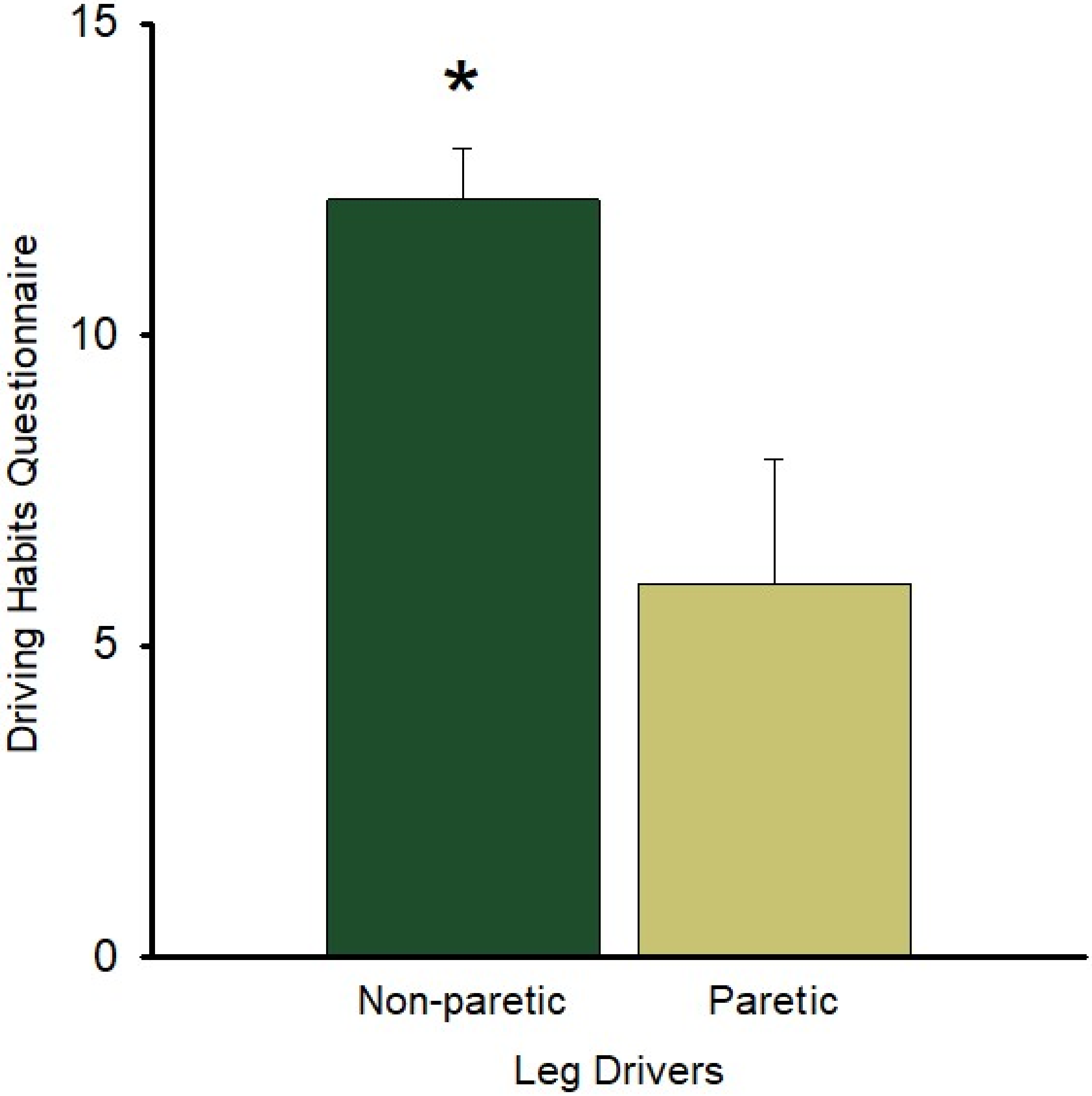

Figure 2.3.3: Self-reported driving habits questionnaire (DHQ) scores. The error bars represent standard error. The individuals who drive with the paretic leg reported significantly worse on-road driving behavior than the individuals who drive with the non-paretic leg. Significance is indicated by *$p < 0.05$.

2.3.4 Neuromuscular activation and coordination of paretic and non-paretic leg drivers

Paretic leg drivers (479.4 ± 96.7 ms) demonstrate significantly longer TA EMG burst duration ($|t_{14}| = -2.5$, $p = 0.01$, $d = 1.3$) compared with non-paretic leg drivers (350.6 ± 102.7 ms), **Figure 2.3.4 A**. TA EMG burst amplitude was comparable ($p = 0.09$) between paretic (55.9 ± 28.7) and non-paretic leg drivers (82.5 ± 44.1), **Figure 2.3.4 B**. Additionally, the two groups demonstrated comparable MG EMG burst duration ($p = 0.12$): paretic (566.0 ± 75.0 ms), non-paretic (509.5 ± 102.0 ms) and amplitude ($p = 0.29$): paretic (65.1 ± 74.0), non-paretic (86.3 ± 68.7), **Figures 2.3.4 C-D**. There were significant differences in muscle coordination as measured by TA-MG Overlap ($|t_{14}| = -2.1$, $p = 0.03$, $d = 1.1$), **Figure 2.3.4 E**. Paretic leg drivers had more TA-MG overlap (1.0 ± 0.4 %) than non-paretic leg drivers (0.6 ± 0.2 %). However, the two groups did not differ in TA-MG Peak Coactivation ($p = 0.48$): paretic (111.8 ± 51.5), non-paretic (93.2 ± 49.7), **Figure 2.3.4 F**. Neuromuscular activation and coordination outcomes were correlated with braking performance, specifically, TA EMG burst duration was positively correlated to brake response time ($r = 0.51$, $p = 0.04$) and motor response time ($r = 0.61$, $p = .01$), **Figures 2.3.5 A-B**. Additionally, TA-MG overlap was significantly positively correlated to brake response time ($r = 0.76$, $p = .001$), **Figure 2.3.5 C**.

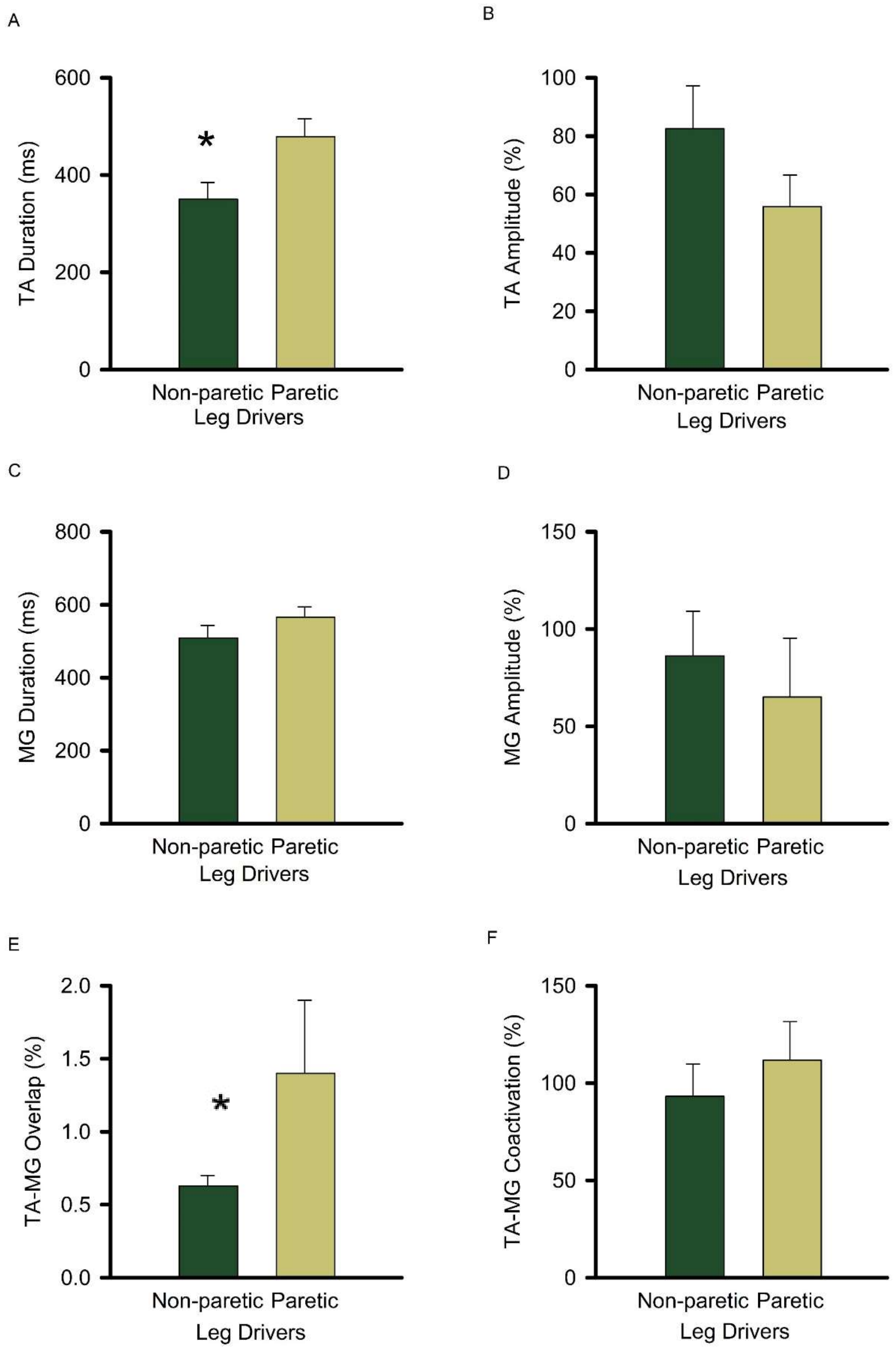

Figure 2.3.4: Neuromuscular activation and coordination during braking. The error bars represent standard error. The individuals who drive with the paretic leg show longer TA EMG burst duration and more TA-MG Overlap than individuals driving with the non-paretic leg. Significance is indicated by *$p < 0.05$.

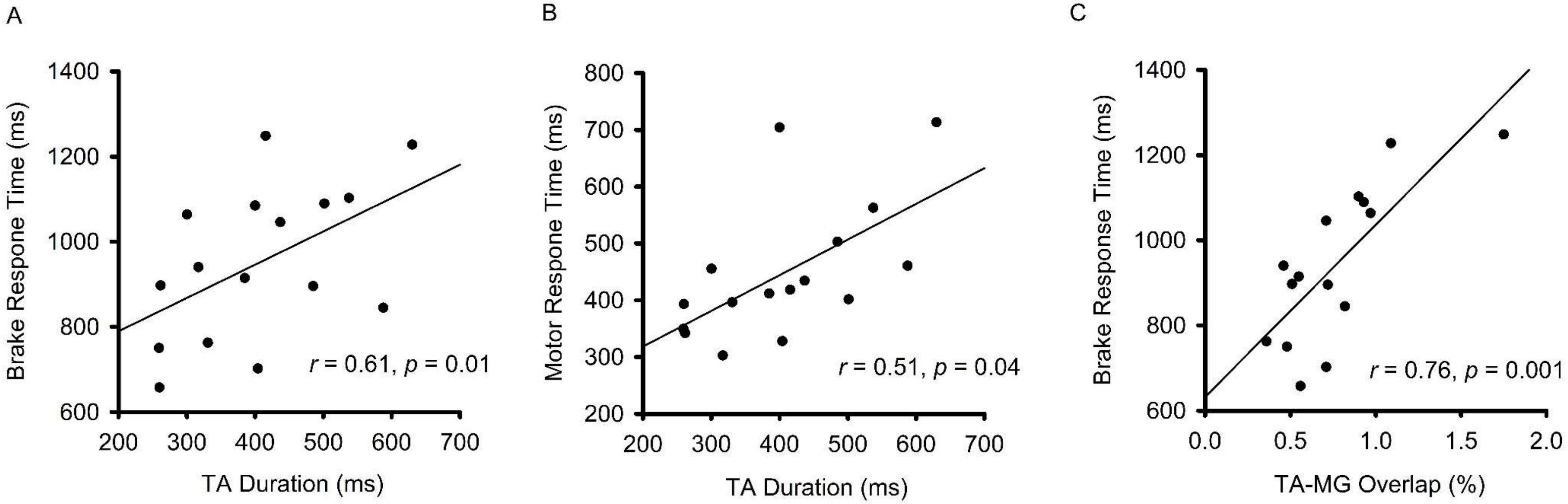

Figure 2.3.5: The relationship of neuromuscular activation and coordination and braking performance . TA Duration is highly positively correlated to brake response time as well as motor respone time. Additionally, TA-MG Overlap is correlated to brake response time. Significance is indicated by $*p < 0.05$.

2.3.5 Driving performance of non-paretic leg drivers: comparing left vs. right leg drivers

Table 2.3.2 shows the clinical characteristics of the individuals who drive with the non-paretic leg. The two groups did not differ on the severity of motor impairments as indicated by FMA-LE, ($|t_9|$ = - 1.11, p = 0.15), and MVC force of dorsiflexion ($|t_9|$ = - 0.33, p = 0.37) and plantarflexion (U = 12.0, z = - 0.38, p = 0.35). Surprisingly, we found no significant differences in car pedal control as indicated by RMSE of the gas pedal ($|t_9|$ = - 0.41, p = 0.34), brake response time ($|t_9|$ = - 0.42, p = 0.34), premotor ($|t_9|$ = 0.03, p = 0.48) and motor response times ($|t_9|$ = - 0.82, p = 0.22), or DHQ (U = 11.0, z = - 0.58, p = 0.28) when comparing non-paretic leg drivers who drive with the left leg versus right leg.

Table 2.3.2: Participant characteristics and driving performance of non-paretic-left leg drivers versus non-paretic-right leg drivers. *FMA-LE – Fugl-Meyer motor assessment for lower extremity; RMSE – Root mean square error; DHQ – Driving habits questionnaire. All scores are mean ± standard deviation*

	Non-Paretic-Left Leg Drivers (*N*=4)	Non-Paretic-Right Leg Drivers (*N*=7)	Statistics (*t/z, p*)
FMA-LE			
Motor (/34)	21.0 ± 6.5	26.0 ± 7.5	(*t* = - 1.11, 0.15)
RMSE of gas pedal (degrees)	11.0 ± 1.8	11.5 ± 2.3	(*t* = - 0.41, 0.35)
Brake Response Time (ms)	847.6 ± 103.3	886.9 ± 169.5	(*t* = - 0.42, 0.34)
Premotor Response Time (ms)	480.1 ± 122.3	477.4 ± 133.8	(*t* = 0.03, 0.48)
Motor Response Time (ms)	367.5 ± 9.4	409.6 ± 77.2	(*t* = - 0.82, 0.22)
DHQ (/15)	11.0 ± 4.1	12.9 ± 1.6	(*z* = - 0.58, 0.28)

2.4. Discussion

The goal of this study was to examine how driving performance in stroke survivors is influenced by paretic versus non-paretic limb use for car pedal control. Individuals with stroke who drove with the paretic leg demonstrate greater gas pedal error, longer brake response time, and longer motor response time than those who drove with the non-paretic leg. Self-reported on-road driving behavior was worse in paretic leg drivers than non-paretic leg drivers. Further, better self-reported driving behavior was associated with shorter brake response time. Interestingly, both stroke groups demonstrated comparable cognitive status and severity of motor impairments. Finally, non-paretic leg drivers who drove with the left leg perform similarly as those who drove with the right leg. Taken together, individuals who drove with the non-paretic leg demonstrate better pedal control than those who drove with the paretic leg. Our study provides novel evidence that the leg selected for driving following stroke impacts the accuracy and the speed of pedal control, as well as self-reported on-road driving behavior.

The number of stroke survivors who drive with the paretic leg is rarely reported. Nevertheless, self-reports of stroke survivors show that adults with right- and left-hemispheric stroke return to driving (Fisk et al., 1997, Perrier et al., 2010). Given that driving typically involves a greater use of the right leg than the left leg, the side affected and the severity of motor impairments after stroke can influence driving performance, and thereby the decision to returning to driving. In the current study, we focused on lower limb specific driving tasks. Since steering often requires the use of both the paretic and non-paretic hands, we purposefully excluded steering from the current study design. By measuring gas and brake pedal control, we aimed to exclusively isolate the impact of the paretic versus non-paretic limb use on driving performance.

2.4.1 Individuals who drove with the paretic leg show increased gas pedal error

The individuals who drove with the paretic leg demonstrated significantly more gas pedal error than the individuals who drove with the non-paretic leg (**Figure 2.3.1**). We used a task involving following a lead car in a driving simulator that required the driver to manipulate the gas and brake pedal to maintain a safe distance from the lead car. This task is similar to following a car in city traffic. Imprecise modulation of the gas pedal can contribute to reduced gap distance between cars and ultimately increase the risk of collision (NSW). Our findings suggest that stroke survivors who use the paretic leg show reduced precision in modulating the gas pedal than those who drive with the paretic leg, thus disposing paretic-leg drivers to higher risk of car crashes.

2.4.2 Individuals who drove with the paretic leg demonstrate longer brake response times and report poor on-road driving behavior.

Braking is a key aspect of safe driving. Fast and accurate braking response can reduce the chance of on-road accidents. Roughly 32% of all traffic accidents are due to rear-end crashes, where inadequate stopping distance contributes to hitting the car ahead (NHTSA, 2007). It has been shown that longer brake response times require more stopping distance and often significantly increase the risk of crash and injury (Montgomery et al., 2014). In our study, the individuals who drove with the paretic leg demonstrated longer brake response times than the individuals who drove with the non-paretic leg. We dissociated the brake response time into premotor response time that measured the speed of identifying and processing the brake lights of the lead car and motor response time that measured the speed of movement execution for braking. We found that both groups showed comparable premotor response times. These results are in line with the similarity between the two groups in the global cognitive status and processing speed on the divided and selective attention. However, the motor response time was significantly longer in the individuals who drove with the paretic leg. These findings suggest that stroke survivors who drove with the paretic leg show delayed brake responses due to slower speed of movement execution rather than impaired speed of processing of the visual stimulus. One explanation for the slower speed of movement execution speed could be altered expression of slower type I myosin heavy chain fibers associated with disuse of the paretic side (Frontera et al., 1997). Additionally, we found that individuals who drove with the paretic leg reported lower on-road driving behavior, that measured driving exposure, space, avoidance, and crashes as compared with those who drove with the non-paretic leg. Importantly, the self-reported driving behavior was negatively correlated with brake response time. These findings suggest that individuals with faster brake response time reported better on-road driving behavior. Together, these findings show that driving performance measured quantitatively through pedal control in simulated driving environment aligned with self-reported on-road driving behavior.

2.4.3 Neuromuscular activation and coordination influences braking performance following stroke

We found that during the braking portion of the car following task, individuals who drove with the paretic leg demonstrated longer TA EMG burst durations as compared to individuals who drove with the non-paretic leg. However, both groups demonstrated similar TA amplitude (**Figures 2.3.4 A-B**). Additionally, we found significantly more temporal overlap of agonist-antagonist muscle in individuals who drove with their paretic leg (**Figure 2.3.4 E**). These differences in neuromuscular activation hold functional significance as TA EMG burst duration is highly positively correlated to both brake response time and motor response time (**Figures 2.3.5 A-B**). The longer TA EMG bust duration would mean a longer period of active dorsiflexion, delaying the ankle plantarflexion required for depressing the brake pedal resulting in longer braking responses. Additionally, TA-MG overlap was significantly positively correlated to motor response time (**Figure 2.3.5 C***)* These correlations highlight the contribution of the motor response time to the longer braking response time seen in individuals who drove with the paretic leg. The increased TA-MG overlap can impair braking speed as both agonist and antagonist muscles are active at the same time, causing the agonist to work against the antagonist to achieve the desired movement. These finding are in line with previous research showing that compared to control, individuals with stroke demonstrate longer TA EMG burst duration and increased TA-MG activation overlap in similarly goal-directed ankle movement tasks leading to decreases in motor accuracy (Lodha et al., 2019). Our finding suggest that individuals driving with their paretic leg show longer TA EMG burst duration and altered co-activation of agonist-antagonist muscles which are related to poorer braking performance.

2.4.4 Driving performance in non-paretic leg drivers was similar regardless of whether right or left leg is used for pedal control

An interesting finding of the current study is that within the non-paretic leg drivers, there were no differences in gas pedal error or brake response times regardless of whether they controlled the pedals with the right or left leg. The lack of differences in the pedal control performance between the two sub-groups of non-paretic leg drivers suggest that driving with the non-paretic left leg enables better pedal control than driving with the paretic right leg. The non-paretic-left leg drivers had an average of 4.4 years of driving experience with car modifications. However, these preliminary findings should be viewed in light of the fact that we had a relatively small sample in each sub-group (**Table 2.3.2**).

Previous studies report that when compared to controls, ischemic stroke survivors with left-side paresis committed significantly more centerline crossings, road edge excursions, and over speeding while individuals with right-side paresis showed no driving deficits (Hird et al., 2018). While the previous study conducted a preliminary comparison of individuals with right- and left-sided stroke to controls, the current study compares performance based on driving leg in individuals with stroke which may explain the discrepancies in results.

2.4.5 Considerations

The current study was the first to examine how pedal control is altered when driving with the paretic or non-paretic leg. Knowing how driving performance may be affected by the choice of driving leg can impact driving safety following stroke and may be an important consideration for driving rehabilitation. As cognitive deficits after stroke can impact driving performance, we purposely focused on a relatively homogenous cohort of individuals with stroke. This homogeneity was determined by similar global cognition and processing speed (divided and selective). This design allowed us to determine limb specific driving impairments that are not influenced by between-subject differences in cognitive status. However, a few limitations are identified. First, the study included a small number of non-paretic drivers who drive with the left leg (N=4). Despite the small sample, these preliminary data may provide some insights on the potential benefits of driving with the non-paretic left leg (often with car modifications) for individuals with right side hemiparesis who want to return to driving safely. Another limitation of this study was that we examined driving performance in only a single scenario i.e., car-following task. To better assess pedal control, future studies should analyze driving performance in different driving environments such as highway, rural, and city driving. Finally, even though simulated driving enables driving assessment in a controlled and safe lab environment, future investigation should examine how pedal control is altered during on-road driving.

2.4.6 Clinical implications

Returning to safe driving is commonly a highly desirable rehabilitation goal following stroke. Previous studies focused on differences in driving between individuals with stroke and healthy controls and revealed distinct deficits in both motor and cognitive domains related to driving performance. (Blane et al., 2017, Groeger and Murphy, 2021, Lodha et al., 2021). However, understanding how the choice of the driving leg influences driving performance is vital for advancing driving rehabilitation after stroke. Our results highlight that driving performance is influenced by the leg selected for pedal control. Specifically, individuals who drive with the paretic leg show increased gas pedal error, slower brake response time, delayed movement execution time, and lower self-reported driving behaviors. To improve driving safety following stroke, driving rehabilitation should consider whether the non-paretic or paretic leg will be used for driving. It has been shown that motor learning is preserved following stroke (Boyd et al., 2007). Therefore, using task-specific motor learning it would be feasible to either relearn pedal control with the paretic leg or train in the new task of pedal control with the non-paretic left leg. The use of task-specific training may be important for neuroplastic change by altering cortical activation resulting in a more normal pattern of brain activation (Boyd et al., 2010). An interesting question for future investigation is to evaluate how targeted rehabilitation based on selected driving leg following stroke can aid in returning to safe driving. Individuals who drive with their paretic leg may benefit from focused training that improves the accuracy and speed of pedal control. Individuals with right-sided hemiparesis may benefit from driving retraining perhaps with the use of car modifications to drive safely with their non-paretic left leg.

2.4.7 Summary

The current study provides novel evidence that driving performance following stroke is influenced by the leg used for pedal control. Individuals who drive with the paretic leg demonstrate exaggerated gas pedal error, longer brake response time, longer motor response times, and self-reported poorer on-road driving behavior. The current findings highlight that driving performance is influenced by the leg used for manipulating the car pedals. These findings point to the importance of accounting for the driving leg in driving rehabilitation protocols to enable individuals with stroke to return to safe driving.

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CHAPTER 3 - MANUSCRIPT 2

The Impact of Cognitive Load on Driving Performance in Individuals with Stroke

3.1. Introduction

Driving is a commonly performed task, however, we seldom drive without engaging in a secondary task. For example, while driving many of us also talk on the phone, listen to music, or have a conversation with a passenger. The engagement in these additional tasks increases the cognitive demand of driving, which is referred to as cognitive load (Engström et al., 2017). Two tasks performed simultaneously, such as driving and talking on the phone is termed dual tasking. In dual tasking, the engagement in one task affects the performance of the secondary task by means of competition for limited neural resources (Thompson et al., 2012). Dual tasking is a method commonly applied in experiments to increase cognitive load and has been widely applied to examine cognitive demands of balance and walking (Baek et al., 2021, Chan and Tsang, 2021). While prior research shows the impact of stroke on driving related skills, the precise influence of increased cognitive load on driving performance in stroke survivors is not known. Evaluation of driving performance with cognitive load may help uncover driving deficits in stroke that may not otherwise be so obvious.

Driving is a cognitively demanding task that involves real time decision making and judgement. Our research group along with others have recently shown that stroke impacts both the cognitive and motor aspects of safe driving such as divided and selective attention, lane maintenance, and brake reaction time (Hird et al., 2018, Lodha et al., 2021). Driving with cognitive dual-task increases the risk of motor vehicle crashes in drivers of all ages (Flaherty et al., 2020, Thompson et al., 2012). Cognitive distractors such as being lost in thought, contribute to 61% of all crashes related to driving with simultaneously participating in another task (Louie and Mouloua, 2019). Studies have shown driving while simultaneously engaging in a working memory tasks leads to impairments in braking response in simulated driving in healthy young individuals (Louie and Mouloua, 2019). Additionally, a study looking at fMRI in healthy controls shows that driving while simultaneously participating in a secondary task causes the brain to sacrifice performance in areas of visual attention and alertness (Schweizer et al., 2013).

Examining the influence of cognitive load on driving performance is vital because an overwhelming 90% of drivers in Colorado self-report driving while distracted by a second task (CDOT). Understanding the influence of cognitive load on driving performance following stoke could reveal cognitive targets for driving rehabilitation not otherwise exposed in lower cognitive load scenarios. Rehabilitation for improving everyday function has primarily focused on motor impairments following stroke. However, the tandem use of motor and cognitive interventions for single- and dual-task walking, balance, and cognition have been shown to be beneficial for performance in healthy and cognitively impaired older adults, as well as neurological patients (Huber et al., 2022). The current study will provide evidence regarding how cognitive load impacts driving performance following stroke.

The aim of the current study is to determine the influence of cognitive load on driving performance in individuals with stroke. We increased the cognitive load during driving by asking individuals to perform a secondary working memory task simultaneously while driving. We selected a working memory task as is it similar to the common everyday task of remembering directions. Driving performance was measured by lane departures, speed compliance, and brake response time in a simulated environment. We hypothesize that compared to single-task driving, dual-task driving with cognitive load will be associated with diminished driving performance indicated by more lane departures, worse speed compliance, and longer brake response time. Understanding the driving impairments in cognitive load situations in individuals with stroke will allow development of more robust driving rehabilitation protocols that focus on both cognitive and motor intervention for restoring safe mobility in individuals with stroke.

3.2. Materials and Methods

Experimental design

This cross-sectional, within-subjects experiment consisted of a single session lasting about one hour that included cognitive, motor, and simulated driving assessments. Participants completed a global cognitive screening assessment followed by motor impairment and strength assessments. Finally, participants completed the driving assessments. First, participants drove in the single-task condition involving driving on a rural road and braking for hazard stimuli. Immediately following single-task driving, individuals completed the dual-task drive which was similar to the single-task drive but included a working memory dual-task.

Ten individuals with stroke participated in the current study. Participant characteristics are presented in **Table 3.3.1.** Inclusion criteria for the individuals with stroke were: (1) diagnosed with a unilateral cerebrovascular accident prior to testing, (2) currently driving or had been driving prior to stroke, (3) ability to generate voluntary ankle plantarflexion and dorsiflexion force, and (4) the ability to understand and follow a three-step command (e.g., “Take this piece of paper in your right hand. Fold it in half. Put the paper on the floor.”). Exclusion criteria were (1) presence of any other neurological or musculoskeletal disorder, (2) pain or injury affecting limb movements, (3) spatial neglect, hearing impairments and global aphasia and (4) history of simulator sickness. The self-reported scores on these impairments were used to screen the participants. All individuals read and signed an informed consent approved by Colorado State University’s Institutional Review Board, prior to participation.

3.2.1 *Cognitive Assessment*

Montreal Cognitive Assessment: To determine global cognitive status, we used the Montreal cognitive assessment (MoCA), a widely used cognitive screening measure. MoCA is scored out of 30, lower scores indicate impaired cognitive status (Nasreddine et al., 2005).

3.2.2 Motor Assessment

Fugl Meyer Assessment: To assess severity of lower extremity motor impairment, we used the lower extremity subsection of the Fugl-Meyer Assessment (FMA). FMA is scored out of 34, lower scores indicate a higher degree of motor impairment.

Strength: The maximal isometric force was quantified during ankle dorsiflexion and plantarflexion. Participants increased force to their maximum in 3 seconds and maintained the maximal force for roughly 3 seconds with 60 seconds rest between successive trials. The participants completed two maximum voluntary contraction (MVC) trials. *Data measurement:* The isometric forces exerted were measured with a handheld dynamometer (model 01165, Lafayette Instrument, Lafayette, IN). We quantified dorsiflexion and plantarflexion strength as the highest value of the MVC force across two trials.

3.2.3 Driving assessments

<u>Simulated Driving Assessment:</u> *Experimental set-up:* Participants sat in a National Advanced Driving Simulator. The simulated driving task was performed with the self-selected driving leg. The foot rested on a customized gas pedal. The simulated driving environment was displayed on three 40-in. computer monitors to deliver a 180-degree field of view (Samsung Electronics America, model: UN40J5500AF, resolution: 1920×1080, refresh rate: 60p Hz).

Task: Participants were instructed to drive along a rural road at 50 MPH and brake as quickly as possible in response to any hazards (e.g., deer, tractor, or dog) that crossed the road unexpectedly. Each trial lasted for ~ 210 seconds. The participants performed a familiarization trial with one hazard stimulus. Then, the participants performed the single-task drive including five hazard stimuli. Finally, participants performed the dual-task drive similar to the singe-task drive while simultaneously performing a working memory task. Here, participants were given the same 3-digit starting number at the start of the trial and asked to subtract 3 and add 4 repeatedly until the drive was complete, answers were recorded. Prior to the dual-task drive, participants practiced the working memory task. Examiners ensured that the participant understood and were able to perform the task.

Data measurement: The force and position from the brake pedal and gas pedal were measured using the CSL Elite Pedals (Fanatec, Endor AG, Germany). All the data were analyzed offline using a custom-written program in Matlab (Math Works Inc, Natick, MA, USA).

Stimulated driving outcome measures:

Lane departures: We determined lane departures as the number of times the bumper of the participant's car deviated out of the designated driving lane throughout the drive. Speed compliance: We measured speed compliance as the percent of time the participant's car was within +/- 5 MPH of the target speed limit of 50 MPH. Speed compliance was calculated between hazard braking events as to avoid including speed at the time of braking. Brake response time: We measured brake response time as the time between the appearance of the hazard stimuli to the application of the brake pedal with a threshold of 10 N. The braking response time was averaged across the five braking events.

3.2.4 Statistical analysis

To determine the influence of cognitive load on simulated driving performance in stroke survivors, we compared the single-task and dual-task driving. We ran a Shapiro-Wilk test to determine whether our data were normally distributed. The variables that were normally distributed (speed compliance) were compared using paired samples *t*-test. The variables that were not normally distributed (lane departures and brake response time) were compared using non-parametric, Wilcoxon Sign Ranked test. The alpha level was set at $p < 0.05$. Effect size is reported with Cohen's d for all t-tests, and r for all Wilcoxon tests*. All* analyses were performed using IBM SPSS 27.0 (IBM, Armonk, NY).

3.3. Results

3.1 Participant characteristics

Table 3.3.1 shows the demographics and clinical characteristics of the individuals. The cross-sectional, within-subject study design enabled each individual with stroke to serve as their own baseline for comparison between single- and dual-task driving.

T*able 3.3.1: Participant characteristics.* *MoCA – Montreal cognitive assessment; FMA-LE – Fugl-Meyer motor assessment for lower extremity; MVC – Maximum voluntary contraction*

	Stroke Survivors (*N*=10)
Age (years)	65.6 ± 14.9
Gender (Female)	6
Hemiparetic side (Left/Right), N	6/4
Time Since Stroke (years)	6.48 ± 4.0
MoCA (/30)	25.5 ± 3.0
FMA-LE	
Motor (/34)	28.9 ± 4.9
MVC force of Driving Leg (N)	
Plantarflexion	143.91 ± 34.96
Dorsiflexion	113.67 ± 27.63

3.3.2 Driving performance

Lane Departures: **Figure 3.3.1** shows the number of lane departures in single- and dual-task driving. We found a significant difference between the two tasks, (z = - 2.50, p = 0.01, r = 0.57) such that the individuals with stroke had more lane departures in dual-task driving (4.0 ± 5.2) than single-task (1.7 ± 2.4) driving.

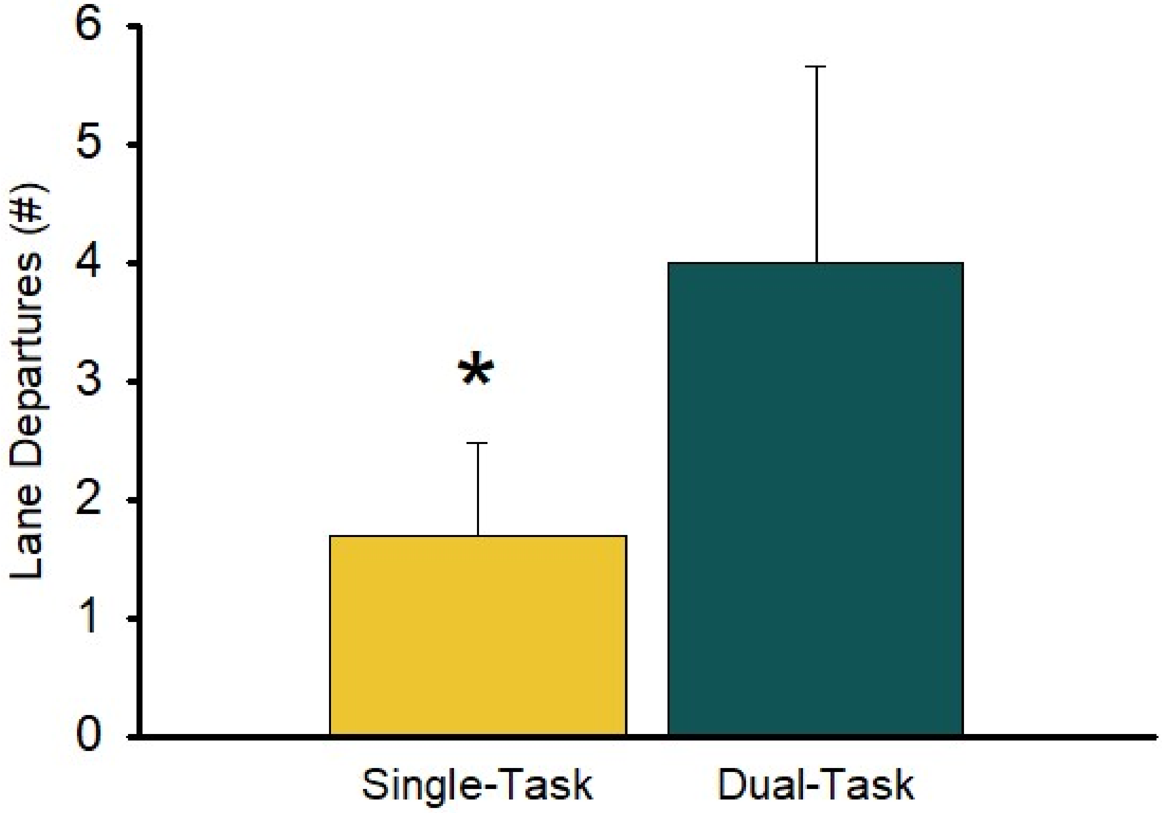

Figure 3.3.1 Lane departures during the single-task and dual-task drives. The error bars represent standard error. We determined lane departures as the number of times the participant's car bumper left the designated driving lane. The individuals with stroke show significantly more lane departures in the dual-task drive than single-task drive. Significance is indicated by *$p < 0.05$.

Speed Compliance: **Figure 3.3.2** shows the speed compliance in single-task and dual-task driving. We found a significant difference between the two tasks, ($|t_9| = 2.00$, $p = 0.04$, $d = 0.77$) such that the individuals with stroke had lower speed compliance in dual-task (49.2 ± 13.9 %) than single-task (60.2 ± 19.6 %) driving.

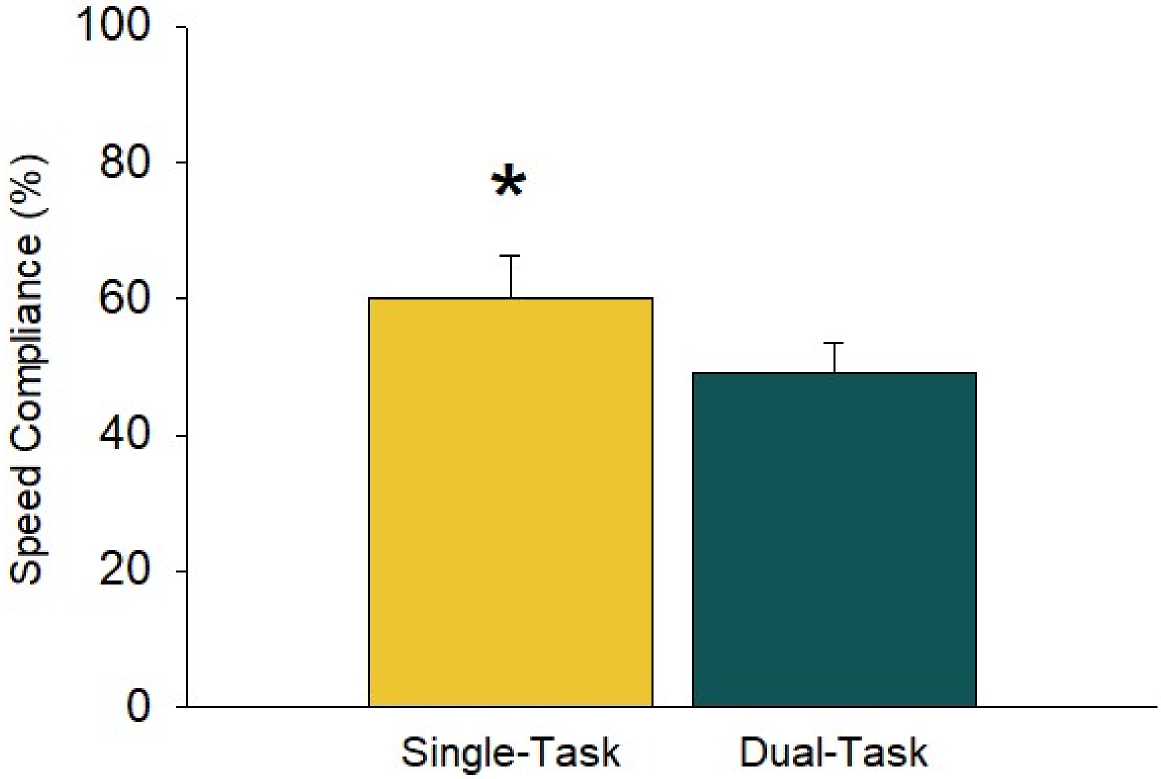

Figure 3.3.2: Speed compliance during the single-task and dual-task drives. The error bars represent standard error. We measured speed compliance as the percent of time the individual was within +/- 5 MPH of the determined speed limit. Speed compliance was significantly worse in the dual-task drive than the single-task drive. Significance is indicated by $^*p < 0.05$.

Brake Response Time: **Figure 3.3.3** shows the brake response time for both tasks. We found no significant difference in brake response time between the single-task (1.15 ± 0.25 s) and dual-task (1.12 ± 0.27 s) driving ($z = -1.27$, $p = 0.10$).

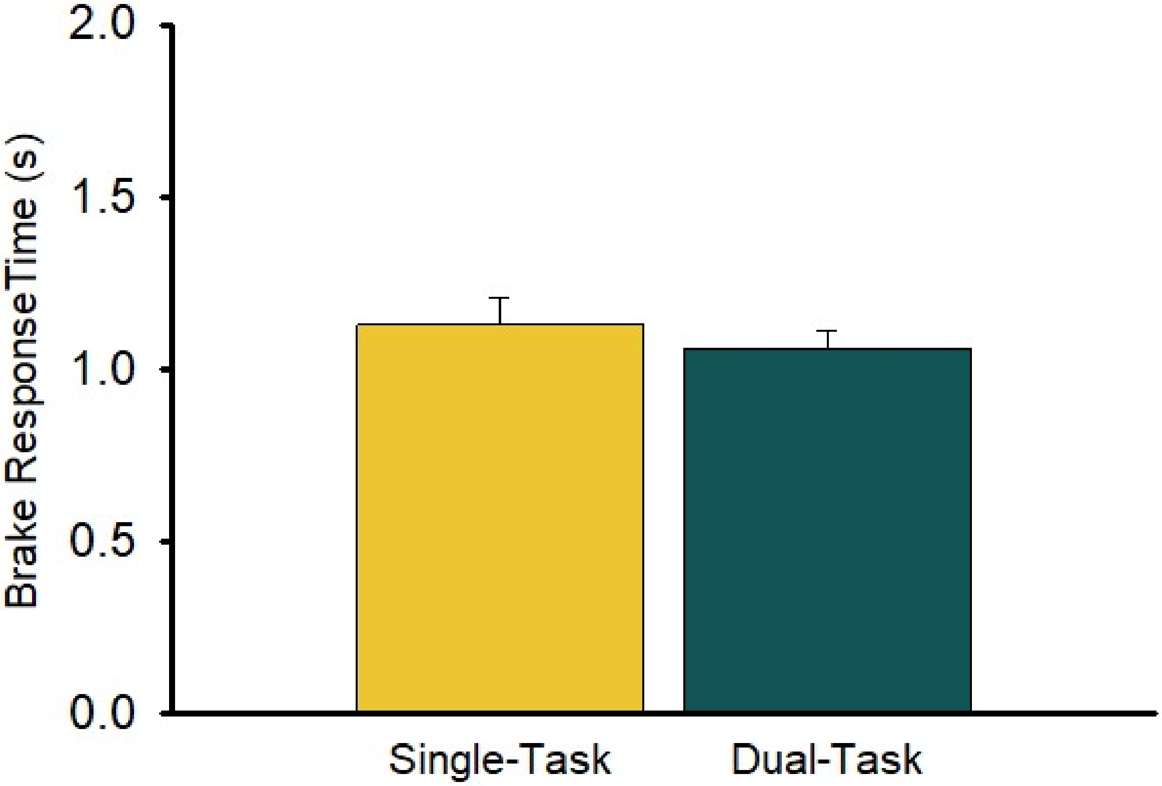

Figure 3.3.3: Brake response time during the single-task and dual-task drives. We measured brake response time as the time between the appearance of the hazard stimuli to the application of the brake pedal with a threshold of 10 N. Brake response time was not significantly different between the single-task and dual-task drives.

3.4. Discussion

The purpose of the current study was to determine the influence of cognitive load on simulated driving performance in stroke survivors. Individuals with stroke demonstrated significantly more lane departures and worse speed compliance during driving with cognitive load. These findings highlight that cognitive load negatively impacts the ability to maintain the car in the driving lane and abide by posted speed limits. Stroke survivors were able to maintain brake response time during dual-task driving suggesting a prioritization of braking in hazard response scenarios. Our study provides novel evidence that cognitive load induced by dual tasking while driving diminished driving performance by impairing lane positioning and speed compliance in individuals with stroke.

3.4.1 Cognitive load during driving increases the total number of lane departures in individuals with stroke

Individuals with stroke demonstrated significantly more lane departures in dual-task driving than single-task driving (**Figure 3.3.1**). Maintenance of lane position is important for avoiding collisions in the surrounding environment. In single lane roads, proper lane position keeps cars from colliding with other environmental objects such as signs, mailboxes or with the on-coming traffic. In two-lane roads, proper lane position is necessary for avoiding collision with neighboring cars. In our study, participants drove on a two-lane road with unexpected moving objects that entered the driving lane. Our findings suggest driving with cognitive load impairs the ability of individuals with stroke to maintain proper lane position by 42% compared to driving without cognitive load. Such impairment in lane positioning leads to an increased number of lane departures, which is detrimental to safe driving and is responsible for 51 % of all traffic fatalities (U.S.DOT, 2022).

3.4.2 *Cognitive load during driving leads to poor speed compliance in individuals with stroke*

Individuals with stroke demonstrated significantly worse speed compliance in dual-task driving than single-task driving (**Figure 3.3.2**). Participants were asked to maintain a speed limit of 50 MPH throughout the drive. Speed compliance was measured between braking events to ensure that that analysis of speed compliance was not influenced by the reduced speed during braking events. In our study, speed compliance was reduced by 122% when driving with cognitive load as compared to single-task driving. Our current findings are in line with previous research showing that in dual-task driving, individuals show performance deficits in following a car of varying speed as well as maintaining a predetermined speed (Bian et al., 2010, Ebnali et al., 2016). Taken together, dual tasking negatively impacts the ability to maintain the speed of the car. Speed compliance is an important factor in safe driving because it reduces the risks associated with driving at dangerously high or low self-selected driving speeds (CDOT, 2002). Varying speeds of different vehicles above or below the speed limit within the same traffic stream leads to compensatory driving behavior like sudden braking and multiple lane changes, both of which increase driving crash risk (CDOT, 2002). Overall, speed compliance is impaired when driving with cognitive load and may increase compensatory behavior and the risk of driving accidents.

3.4.3 *Brake response time is not influenced by cognitive load during driving*

An interesting finding of this study is that brake response time is not influenced by dual-task driving in individuals with stroke (**Figure 3.3.3**). We used a hazard braking task in a driving simulator that required individuals to apply sufficient brake force to avoid hitting the objects that cross their driving path. Participants were asked not to swerve but instead brake to avoid hitting the object. One explanation for these finding could be the nature of the driving task used to test driving performance in the current study. The biggest threat for our drivers in the scenario was the potential of crashing into one of the hazard stimuli. Perhaps, the participants prioritized braking in the dual-task drive to avoid collision. This is congruent with previous meta-analyses that investigated effects of a working memory task on brake performance in response to unexpected objects (pedestrians, bicycles, etc), similar to our hazard stimuli (Engström et al., 2017, Horrey and Wickens, 2006). The theoretical explanation for these results is that the demand or urgency of braking for a hazard or looming object is sufficient to force the individuals to prioritize the braking task. However, our findings are inconsistent with other previous research showing increase braking times during dual-task driving in young adults (Broeker et al., 2020). These seemingly disparate results may be because of the distinct populations in each study. In the current study, our participants were older and exhibited motor deficits. Awareness of age and stroke-related decline in function may contribute to cautionary behavior and increased emphasis on braking to avoid collisions (Falkenstein et al., 2020).

3.4.4 *Considerations*

While the effect of cognitive load on driving has been examined in healthy younger and older adults, the current study is the first to examine how driving performance is influenced by cognitive load in individuals with stroke. Understanding the influence of increased cognitive load on driving performance in individuals with stroke may provide important insights for driving rehabilitation post-stroke; however, a few limitations are identified in the current study. First, the sample size in this pilot study is relatively small to draw strong conclusions regarding the impact of cognitive load on driving performance post-stroke. Second, even though the working memory, arithmetic task provided sufficient cognitive load, the task had limited real world applications. In future studies, the use of music or cellular devices may be a better representation of real-world cognitive tasks. Finally, the simulated driving scenario did not have additional oncoming or same-direction traffic. Therefore, future studies should make the driving environment as similar to on-road driving as possible. Overall, driving with cognitive load such as while listening to and remembering directions or reading multiple road signs is common. Therefore, retraining individuals with stroke to drive safely with cognitive load could promote greater engagement in safe driving.

3.4.5 *Clinical Implications*

Driving is crucial for maintaining independence. Therefore, returning to safe driving following stroke is often a common rehabilitation goal. Previous studies revealed that driving performance is impacted by cognitive and motor deficits following stroke (Baek et al., 2021, Chan and Tsang, 2021, Hird et al., 2018, Lodha et al., 2021). A recent study showed the efficacy of motor training in improving braking during driving in stroke survivors (Lodha et al., 2022). The study showed that motor rehabilitation was associated with faster movement execution time during braking. However, cognitive processing time for braking remain unchanged, leading to no significant change in the overall braking time. The current study shows that cognitive load impacts driving performance and provides rationale that an additional cognitive training could lead to further improvements in braking performance. Understanding how driving in a high cognitive load scenario influences driving performance in individuals with stroke is important to develop effective driving rehabilitation protocols. Our results identified that individuals with stroke show more lane departures and worse speed compliance in dual-task driving than single-task driving. To improve driving safety following stroke, driving rehabilitation should focus on the cognitive load associated with dual-task driving. An interesting question for future investigations is to determine if a cognitive training with varying cognitive load during driving rehabilitation could enhance driving performance and potentially lead to reduced incidence of driving errors in stroke survivors.

3.4.6 *Summary*

The current study provides novel evidence that driving performance following stroke is impacted by cognitive load. We found that individuals with stroke demonstrated more lane departures and worse speed compliance in dual-task driving than single-task driving. Importantly, individuals with stroke were able to preserve brake response time while driving with cognitive load, demonstrating a task prioritization of timely braking. These findings highlight the driving performance may vary based on cognitive load in the stroke population and point to the importance of including cognitive training in individuals with stroke who wish to return to safe driving.

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CHAPTER 4 - CONCLUSION

Individuals with stroke experience both motor and cognitive deficits. Often these deficits impact stroke survivors' ability to drive, depriving them of independence. However, stroke-related deficits can be unique between individuals and evaluating how specific motor and cognitive factors may influence driving performance in stroke survivors is vital for developing effective driving rehabilitation strategies. The current studies highlight the influence of the motor and cognitive deficits on driving performance following stroke. Study 1 examined the influence of limb selection for gas and brake pedal control on driving performance. Our findings suggest that individuals with stroke who use their paretic leg for pedal control demonstrate poor gas pedal control and longer braking times than those who use the non-paretic leg. These findings point to the need of considering the limb that will be used for pedal control for effective driving rehabilitation strategies. Perhaps individuals who experience right-side paresis may need training to improve accuracy and speed of movement if they plan to use paretic leg for driving, while others may benefit from re-learning to drive with the non-paretic left leg using car modifications. Study 2 examined the influence of cognitive load, induced by a dual-task (simultaneous working memory task) on driving performance in individuals following stroke. Finding from this study suggest that stroke survivors demonstrate impaired driving performance in dual-task driving compared with single-task driving. Specifically, stroke survivors show difficulty maintaining lane position and speed limits. These results emphasize the need to incorporate cognitive training, in addition to motor training in driving rehabilitation protocols to prepare individual with stroke to return to safe driving. The current studies demonstrate that the need to assess and train motor and cognitive deficits that contribute to driving performance in individuals with stroke. Limb selection for pedal control and cognitive load impacts the driving performance of individuals with stroke. To promote safe mobility and restore the independence, driving rehabilitation strategies focused on motor and cognitive capabilities should be considered for individuals with stroke.

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