1-1-2016

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Accepted version. *Journals of Gerontology. Series A: Biological Sciences & Medical Sciences*, Vol 71, No. 12 (2016): pg. 1676-1681. DOI.

Motor Output Variability Impairs Driving Ability in Older Adults

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Abstract

Background: The functional declines with aging relate to deficits in motor control and strength. In this study, we determine whether older adults exhibit impaired driving as a consequence of declines in motor control or strength.
Methods: Young and older adults performed the following tasks: (i) maximum voluntary contractions of ankle dorsiflexion and plantarflexion; (ii) sinusoidal tracking with isolated ankle dorsiflexion; and (iii) a reactive driving task that required responding to unexpected brake lights of the car ahead. We quantified motor control with ankle force variability, gas position variability, and brake force variability. We quantified reactive driving performance with a combination of gas pedal error, premotor and motor response times, and brake pedal error.
Results: Reactive driving performance was ~30% more impaired ($t = 3.38$; $p < .01$) in older adults compared with young adults. Older adults exhibited greater motor output variability during both isolated ankle dorsiflexion contractions ($t = 2.76$; $p < .05$) and reactive driving (gas pedal variability: $t = 1.87$; $p < .03$; brake pedal variability: $t = 4.55$; $p < .01$). Deficits in reactive driving were strongly correlated to greater motor output variability ($R^2 = .48$; $p < .01$) but not strength ($p > .05$).
Conclusions: This study provides novel evidence that age-related declines in motor control but not strength impair reactive driving. These findings have implications on rehabilitation and suggest that interventions should focus on improving motor control to enhance driving-related function in older adults.

Key words: Driving issues, Functional performance, Motor control, Physical function, Motor output variability

Motor control is vital to many activities of daily living.[1–3] It is classically quantified with motor output variability that is defined as the unintentional variation in the output of voluntary contractions.[4] The functional significance of motor output variability is that it is associated with impaired movement accuracy.[5] Older adults exhibit deficits in motor control[4] with detrimental consequences in activities of daily living.[1–3] In addition to the deterioration in motor control, age-related declines in strength also have been related to functional impairments.[6,7] Here, we examine whether age-related declines in motor control or strength impair the driving ability of older adults.

We chose reactive driving as our model functional task because driving is performed everyday by millions of individuals. Reactive driving is essential for car following,[8] which requires responding to unexpected stimuli with accurate and consistent movements. For example, following a car requires consistent control of the gas pedal.[9] In addition, responding to unexpected brake lights of the car ahead requires precise and consistent control of the brake pedal.[10] Increased motor output variability on the gas and brake pedals can influence car velocity and consequently compromise the safe distance between the two cars.

Interestingly, our reactive driving task combines visuomotor tracking (gas pedal control) and goal-directed movements (brake control), which we and others have examined in the laboratory.[11–14] Furthermore, the age-related increase in motor output variability has been extensively documented for these tasks.[4,15] Typically, variability during visuomotor tracking tasks is greater in older adults.[4,16] These findings appear to be consistent at very low force levels (<5% maximum)[15–17] and with high amount of visual information.[13,18] Variability during goal-directed tasks is also greater in older adults, and this finding is consistent across all force levels[19] and joint movements.[12] Nonetheless, the consequence of greater motor output variability on the driving ability in older adults has not been clearly demonstrated.[20]

The age-related decline in functional capacity has also been related to deterioration in strength.[6,7] Thus, another interest of this study was to determine whether age-related changes in strength influence reactive driving performance, independent of the increased motor output variability. Evidence suggests that declines in strength and motor control are independent in older adults.[21] For example, older adults exhibit similar strength with young adults but significantly greater motor output variability.[4,22–24] Therefore, age-related changes in strength could influence reactive driving performance in older adults independent of motor output variability.

The goal of this study was to determine whether older adults exhibit impaired reactive driving as a consequence of greater motor output variability or lesser strength than young adults. We tested the hypothesis that greater motor output variability in older adults is the significant contributor to impaired reactive driving performance.

Methods

Participants

Twelve young (age = 22.75±3.69 years, 7 males and 5 females) and 16 older (age = 72.69±7.40 years, 9 males and 7 females) adults volunteered to participate in this study. All participants were current drivers, with normal or corrected vision, and reported being healthy without any known neurological or musculoskeletal problems. Prior to participation, all individuals read and signed an informed consent approved by the University of Florida's Institutional Review Board.

Experimental Approach

Participants performed two tasks during the experimental session. The first was an isolated visuomotor tracking task and the second was a reactive driving task. The session lasted ~2 hour. Each participant performed the following procedures within a session: (i) maximal voluntary contraction (MVC) tasks; (ii) visuomotor tracking trials involving 3 practices and 10 test trials; and (iii) reactive driving task involving 3 practices and 10 test trials. All tasks were performed with the right foot.

Maximal Voluntary Contraction

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 ~3 seconds with 60 seconds rest between successive trials. The participants completed three to five MVC trials or until two MVC trials were within 5% of each other. We quantified the MVC as the average of the two highest MVCs. The order of the plantarflexion and dorsiflexion MVC was randomized between participants. MVC tasks were repeated at the end of the experimental session to assess if fatigue was induced.

Isolated Visuomotor Tracking Task

Experimental Setup

Participants were seated comfortably in an upright position in front of a 32-inch monitor (Sync Master 320MP-2; Samsung Electronics America; resolution: 1,920×1,080; refresh rate: 60p Hz) that provided the visual feedback of the isometric forces produced by the ankle dorsiflexion. The hip joint was flexed to ~90° with 10° abduction, the knee was flexed to ~45°, and the ankle was plantarflexed to ~15°. The foot rested on a customized foot device with an adjustable foot plate and was secured by straps over the metatarsals to ensure a secure position and simultaneous movement between the device and the foot (Figure 1A).

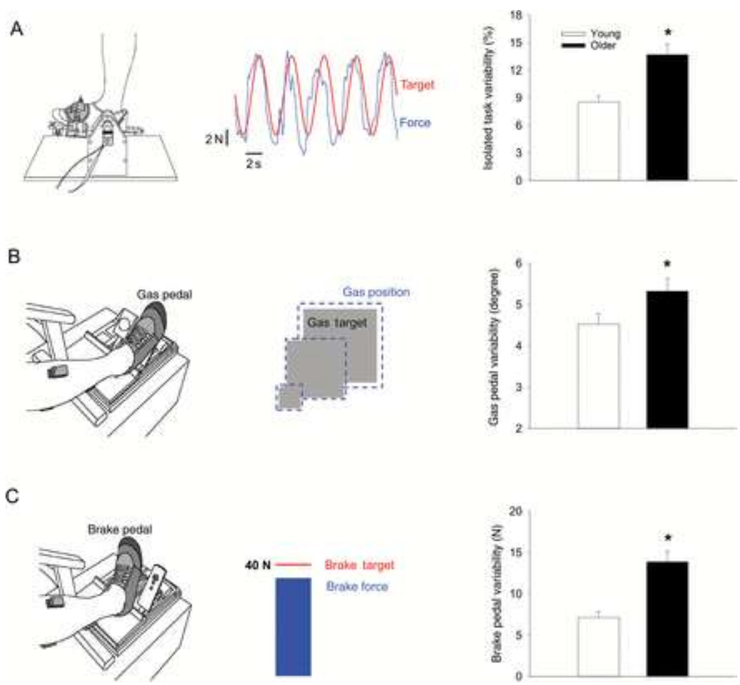

Figure 1. Motor output variability. (**A**) Left: isolated visuomotor task to control isometric ankle force. Middle: the participants performed visuomotor tracking of a sinusoidal target (gray line; at 0.5 Hz from 20 to 30 N at 15% maximal voluntary contraction) by exerting ankle force (blue line). Right: the variability during the isolated task was significantly greater in older adults. (**B**) Left: functional visuomotor task to control the gas pedal with ankle movement. Middle: the participants tracked a gray box (target; at 0.5 Hz through a 10° range of motion) by controlling the gas pedal (black dotted line). Right: the gas pedal variability was significantly greater in older adults. (**C**) Left: functional goal-directed task to exert a precise force on the brake pedal. Middle: the participants aimed to exert a force (black; single trial) on the

brake pedal (gray; target = 40 N) across 10 trials. Right: the brake pedal variability among trials was significantly greater in older adults.

Task

The participants tracked a sinusoidal target at a frequency of 0.5 Hz by producing isometric ankle dorsiflexion forces (Figure 1A). A total of 13 trials were performed. The first three trials were familiarization trials and excluded from the analysis. Each trial lasted for ~35 seconds. Rest period of 90 seconds was provided between consecutive trials to minimize fatigue.

Force Measurement

The isometric forces exerted during ankle dorsiflexion was measured with a force transducer (model 41BN, Honeywell, Morristown, NJ) that was located parallel 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.

Reactive Driving Task

Experimental Setup

Participants were seated comfortably in an upright position in front of a 32-inch monitor (Sync Master 320MP-2, Samsung Electronics America, resolution: 1920×1080, refresh rate: 60p Hz) that provided visual feedback from (i) ankle dorsiflexion movements on the gas pedal and (ii) force on the brake pedal. The foot rested on a customized gas pedal. The hip joint was flexed to ~90° with 10° abduction, the knee was flexed to ~45°, and the ankle was plantarflexed to ~15°.

Task

Participants were instructed to track a visual target by controlling the gas pedal with right ankle movements (see Supplementary Materials). While performing this task, the rear lights of the car in front lighted up (red) at a random time. Participants reacted to this visual stimulus as fast as possible by moving the foot from the gas pedal to the brake pedal and exerted a brake force of 40 N. Participants performed a total of 13 trials. The first three trials were familiarization trials and excluded from the analysis. Each trial lasted 20 seconds with a rest period of 60 seconds between consecutive trials.

Pedal Position and Force Measurement

The force from the brake pedal was measured using a force transducer (Model LAU200, 100 lbF 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).

Data Analysis

Motor Output Variability

We quantified motor output variability during an isolated ankle dorsiflexion task and during reactive driving task. For the isolated visuomotor task, the force signal was band-pass filtered between 0.4 and 0.6 Hz to remove the task-related frequency (sinusoidal target at 0.5 Hz). The magnitude of force variability within each trial was quantified as the coefficient of variation of force (coefficient of variation of force = standard deviation of force/mean force output × 100).

For the reactive driving task, we measured the positional variability on the gas pedal and force variability of the brake pedal. The gas pedal variability was quantified as the standard deviation of the gas pedal position. The gas pedal position was band-pass filtered 0.4–0.6 Hz to remove the task-related frequency. The brake pedal variability was quantified as the standard deviation of the brake force produced by each participant across 10 trials.

Reactive Driving Performance

The four components of the reactive driving task performance included gas pedal error, premotor response time, motor response time, and brake pedal error (see Supplementary Materials). Gas pedal error was quantified as the positional accuracy of gas pedal. We computed the root mean square error of the gas pedal position from the target. Premotor response time was quantified as the time between the onset of the visual stimulus and initial activation of the tibialis anterior muscle. Motor response time was quantified as the time between the initial activation of the tibialis anterior muscle and the brake force onset. Brake pedal error was quantified as the error in the exerted peak force relative to the targeted force (40 N) on the brake pedal.

A greater score on any of the four components of reactive driving performance indicated poorer performance. These four components were specifically chosen to compute the reactive driving score because the participants were instructed to modulate their performance on these measures by tracking a visual target with the gas pedal as accurately as possible (gas pedal error), quickly respond to the red lights (premotor response time) by moving the foot from the gas pedal to the brake pedal (motor response time), and applying a precise amount of force (brake pedal error).

The overall reactive driving score was quantified as the average score from the four components described above. To achieve this, we performed the following processing for each of the four components: (i) we computed the group average by obtaining a mean across all the participants tested in this study. (ii) We normalized the score for each participant by dividing individual scores with the group average. The overall reactive driving score for each participant was computed by averaging the four components of reactive driving. Thus, a higher reactive driving score reflected poorer reactive driving performance.

Statistics

We compared young and older adults using independent *t*-test on the following measures: (i) motor output variability (coefficient of variation of force during isolated visuomotor task, standard deviation of the gas and brake pedal variability during reactive driving); (ii) strength (MVC during ankle dorsiflexion and plantarflexion); (iii) components of reactive driving performance (gas pedal error, premotor response time, motor response time, brake pedal error); and (iv) the reactive driving score. We examined the relation between strength, motor output variability, and reactive driving performance by conducting Pearson's bivariate correlations. We used a stepwise multiple-linear regression model to predict the reactive driving score (dependent variable; criterion) from the participant's strength, gas pedal variability, and brake pedal variability (independent variables; predictors). The squared multiple correlation (R^2) and the adjusted squared multiple correlation (adjusted R^2) determined the goodness-of-fit of the model. All statistical tests were conducted with an alpha level set at 0.05 using the IBM SPSS Statistics 21.0 statistical package.

Results

Strength and Motor Output Variability

The strength was not significantly different between the two age groups for both the dorsiflexion ($|t_{26}| = -1.64$; $p > .05$) and plantar flexion ($|t_{26}| = -1.43$; $p > .05$) MVC tasks. The MVC force during the dorsiflexion was 116.18±40.75 N for the older adults and 142.5±43.45 N for the young adults, whereas the MVC force during the plantarflexion was 118.81±40.58 N for the older adults and 148.33±67.95 N for the young adults.

The force variability during the isolated visuomotor task was significantly greater in older adults (Figure 1A; $|t_{21.17}| = 2.76$; $p < .05$). The positional variability of the gas pedal was significantly greater in older adults (Figure 1B; $|t_{26}| = 1.87$; $p < .03$). Finally, the force variability on the brake pedal also was greater in older adults (Figure 1C; $|t_{22.61}| = 4.55$; $p < .01$).

Reactive Driving Performance

We compared young and older adults on the four reactive driving components—gas pedal error, premotor response time, motor response time, and brake pedal error. The gas pedal error (Figure 2A; $|t_{26}| = 1.83$; $p < .05$), the premotor response time (Figure 2B; $|t_{20.98}| = 2.21$; $p < .05$), and the brake pedal error (Figure 2D; $|t_{23.67}| = 2.35$; $p < .05$) were significantly greater in older adults. The motor response time was not significantly different between the two age groups (Figure 2C; $p > .05$). We computed an overall index of reactive driving by averaging the normalized values for the four reactive driving components. The older adults exhibited significantly greater overall reactive driving score compared with the young adults (Figure 3; $|t_{24.61}| = 3.38$; $p < .01$), which reflected poorer reactive driving performance (see the Methods section for quantification).

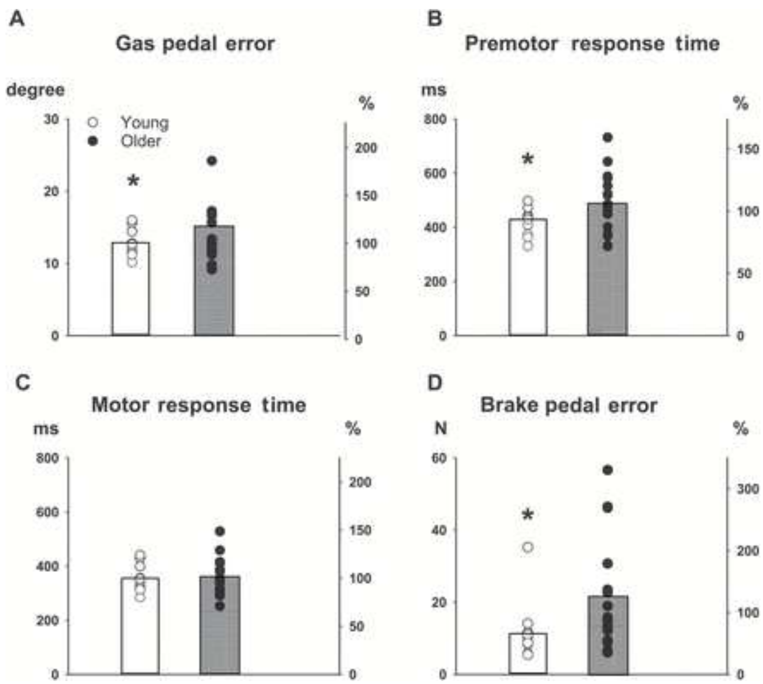

Figure 2. Components of reactive driving performance. For all figures, the axis on the left indicates the actual performance score, whereas the axis on the right demonstrates the performance normalized to the mean of all the participants. (**A**) Gas pedal error quantifies the error of gas pedal position relative to the target. (**B**) Premotor response time quantifies the time between the onset of the stimulus to the onset of muscle activity. (**C**) Motor response time quantifies the time between the onset of the muscle activity to the onset of brake force. (**D**) Brake pedal error quantifies the error of brake pedal force relative to the target. Older adults exhibited significantly greater gas pedal error, premotor response time, and brake pedal error. The motor response time was not significantly different between groups.

Journals of Gerontology. Series A: Biological Sciences & Medical Sciences, Vol 71, No. 12 (2016): pg. 1676-1681. DOI.

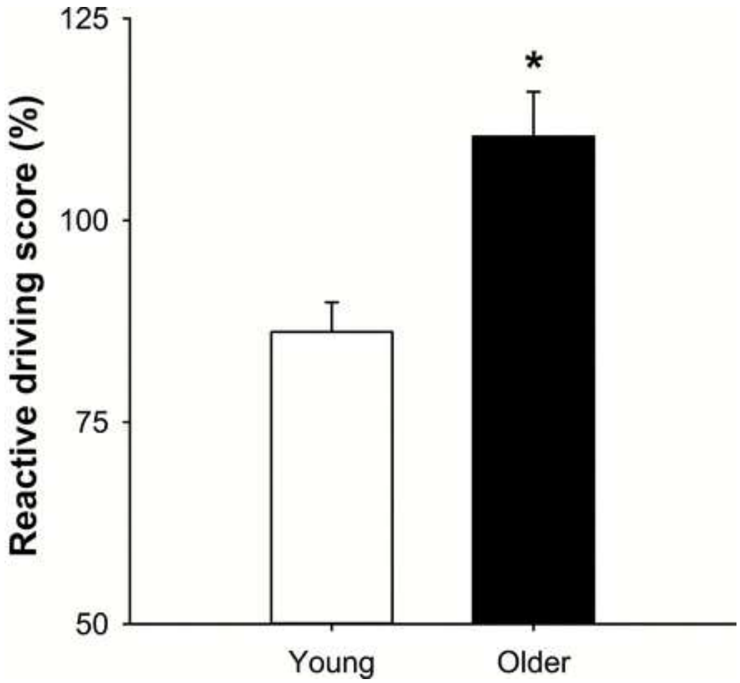

Figure 3. Overall reactive driving performance. The overall reactive driving score was computed as the average normalized score from the four components of reactive driving performance (described in Figure 2). The reactive driving score was significantly greater in older adults, indicating poorer reactive driving performance.

Strength, Motor Output Variability, and Reactive Driving Performance

The reactive driving score was not correlated to ankle dorsiflexion and plantarflexion strength ($p > .05$). In contrast, the reactive driving score was positively correlated with the isolated task variability (Figure 4A; $r = .48$, $p < .05$), gas pedal variability (Figure 4B; $r = .45$, $p < .01$), and brake pedal variability (Figure 4C; $r = .69$, $p < .01$). Furthermore, the reactive driving score was significantly predicted only from brake pedal variability ($R^2 = .48$, adjusted $R^2 = .46$; $p < .05$; Figure 4D). This regression model indicated that greater brake pedal variability was associated with poorer reactive driving score.

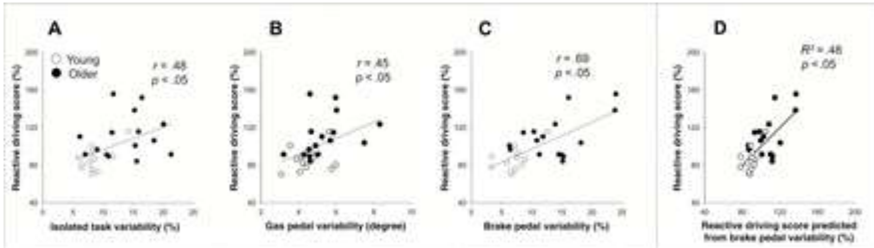

Figure 4. Motor output variability and reactive driving performance. Reactive driving score was positively correlated with isolated task variability (**A**), gas pedal variability (**B**), and brake pedal variability (**C**). Reactive driving score was not related to the maximal voluntary contraction strength during ankle dorsiflexion. (**D**) Stepwise multiple-linear regression model was applied to predict the reactive driving score (dependent variable) from the brake and gas pedal variability and strength of each participant (independent variables). The model predicted (R^2 = .48) the brake pedal variability as the primary predictor of reactive driving score.

Discussion

The purpose of this study was to determine whether reactive driving performance deteriorates in older adults because of declines in motor control or strength. We demonstrate that reactive driving is ~30% more impaired in older adults relative to young adults. This functional deficit in older adults was related to impairments in motor control but was not related to declines in strength. Thus, for the first time in the aging literature, we provide evidence that greater motor output variability is a significant contributor to driving deficits in older adults.

Motor Output Variability and Reactive Driving

Driving is critical for maintaining mobility and functional independence in older adults. In this study, we examined a reactive task that is experienced frequently during every day driving. For example, driving often requires maintenance of a safe distance from the car ahead. This driving situation, termed car following, necessitates responding to the car ahead by controlling the gas and brake pedals with robust consistency. Aging-related increase in motor output variability[4,12–15,17–19,25] reduces the consistency on the gas and brake pedal. Increased force variability (see Figure 1C) could result in lesser force on the brake pedal and significantly increase the distance required to bring the car to a complete stop leading to a collision. Furthermore, increased movement variability from the gas pedal to the brake pedal may slow the response time. Therefore, increased motor output variability in older adults may be linked to greater chances for driving accidents.

One of the most interesting findings in this article is that the reactive driving performance in older adults is strongly predicted from motor output variability. The reactive driving score was computed as an overall index of performance from measures other than motor output variability. Specifically, we quantified this score from parameters that the participants were explicitly instructed to control (gas pedal accuracy, premotor time, motor time, and brake pedal force error). In addition, the association between greater motor output variability and poorer reactive driving performance was demonstrated from the variability during the isolated ankle task. Thus, the independence of motor output variability and reactive driving score strengthens the proposition that greater motor output variability is a significant contributor to impaired reactive driving in older adults.

Numerous studies have demonstrated that impaired driving in older adults relates to cognitive deficits.[26,27] Our findings provide the first evidence that motor control deficits also contribute significantly to driving impairments in older adults. Thus, our findings support and extend previous work in the aging literature, which demonstrates that greater motor output variability is associated with diminished function in humans. For example, increased variability in the motor system has been linked to deficits in manual dexterity[2] and reduced balance and postural control.[28] The greater motor output variability in older adults may result from increased sensory or motor noise.[29] Increased sensory noise in older adults is demonstrated from greater variability in the firing of muscle spindles,[30] and increased motor noise is demonstrated from greater motor unit discharge rate variability.[15] Therefore, motor output variability is an index of increased noise in the central nervous system that interferes with sensory input, planning, and execution of the motor command that influences functional capacity.[29]

Strength Declines and Reactive Driving

Strength is typically used as a clinical indicator of functional impairment.[6] In this study, we found that reactive driving performance was not related to strength. These results are in line with two sets of data: (i) Despite differences in motor control, older adults are not always weaker than young adults[4,22–24,31] and (ii) in older adults, training-related increase in strength was independent of reductions in force variability.[21,32] These findings suggest that motor output variability and muscle strength are independent in older adults. Indeed, we support this finding by showing no association between strength and motor output variability and by providing evidence that reactive driving performance is related to motor output variability but not strength. A possible explanation for the contribution of motor output variability is that our reactive driving task requires robust force control than strength capacity.

Considerations

Reactive driving is a relatively small component of overall driving. Future research should examine the contribution of motor output variability to on-road driving performance in older adults. In addition, future studies should identify training protocols to reduce motor output variability in older adults. Potentially, reductions in motor output variability will result in more meaningful improvements in functional tasks.

In conclusion, we provide novel evidence that a decline in motor control and not strength impairs reactive driving in older adults. The age-related decline in motor control is demonstrated with greater motor output variability during isolated laboratory tasks and functional driving tasks. We conclude that driving rehabilitation in older adults will benefit from a reduction in motor output variability.

Funding

The funding was supported by American Heart Association's Scientist Development Award 14SDG20450151 to N.L.

Conflict of Interest

The authors declare no competing financial interests.

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