Effectiveness of Compensatory Vehicle Control Techniques Exhibited by Drivers after Arthroscopic Rotator Cuff Surgery

Mariette Brink Metrey

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Miguel A. Perez, Chair
Zachary R. Doerzaph
Sheila G. Klauer

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ABSTRACT

Current return-to-drive recommendations for patients following rotator cuff repair (RCR) surgery are not uniform due to a lack of empirical evidence relating driving safety and time-after-surgery. To address the limitations of previous work, Badger et al. (2022) evaluated, on public roads, the driving fitness of patients prior to RCR and at multiple post-operative timepoints. The goal of the Badger, et al. study was to make evidence-based return-to-drive recommendations in an environment with higher fidelity than that of a simulator and not subject to biases inherent to surveys.

Badger et al., however, do not fully investigate the driving practices exhibited by subjects, overlooking the potential presence of compensatory driver behaviors. Further investigation of these behaviors through observation of direct driving techniques and practices over time can specifically answer how drivers may modify their behaviors to address a perceived state of impairment. Additionally, the degree of success in vehicle operation by comparing an ideal turn to the path taken by the driver allows for a level of quantification of the effectiveness of the compensatory techniques. Moreover, driver trajectories inferred from the vehicle Controller Area Network (CAN) metrics and from global positioning system (GPS) coordinates are contrasted with the ideal turn to assess minimum requirements for future sensors that are used to make these trajectory comparisons.

This investigation leverages pre-existing data collected by the Virginia Tech Transportation Institute (VTTI) and Carilion Clinic as used in the analysis performed by Badger et al. (2022). RCR patients (n=27) executed the same prescribed driving maneuvers and drove the same route in a preoperative state and at 2-, 4-, 6-, and 12-weeks post operation. Behavioral data were annotated to extract key characteristics of interest and related them to relevant vehicle sensor readings. To construct vehicle paths, data was obtained from the on-board data acquisition system (DAS).

Behavioral metrics considered the use of ipsilateral vehicle controls, performance of non-primary vehicle tasks, and steering techniques utilized to assess the impact of mobility restrictions due to sling use. Sling use was found to be a significant factor in use of the non-ipsilateral hand associated with the operative extremity (i.e., operative hand) on vehicle functions and, in particular, difficulty with the gear shifting control. Additionally, when considering the performance of non-primary vehicle tasks as assessed through a prescribed visor manipulation, sling use was not a significant factor for the task duration or completion of the task in a fluid motion. Sling use was, however, significant with respect to operative hand position prior to the completion of the visor manipulation: the operative hand was often not on the steering wheel prior to the visor maneuver. In addition, the operative hand was never used to manipulate the visor when the sling was worn. One-handed steering was also more frequent with the presence of the sling.

Further behavioral analysis assessed the presence of compensatory behavior exhibited by subjects during periods in which impairment was perceived. Perceived impairment was observed as a function of the different experimental timepoints. Findings indicated a significant decrease in the lateral vehicle jerk during post-operative weeks 6 and 12. Significant differences, however, were not observed in body position alteration to avoid contact with the interior vehicle cabin, in over-the-shoulder checks, and in forward leans during yield and merge maneuvers.

Regarding trajectory analysis, sling use did not produce a significant difference in the error metrics between the actual and ideal paths. In completion of turning maneuvers, however, operative extremity was significant for left turns, with greater error against the ideal path observed from those in the left operative cohort compared to those in the right operative cohort. For the right turn, however, operative extremity was not found to be a significant factor. In addition, the GPS data accuracy proved insufficient to support comparison against the ideal path.

Overall, findings from this study provide metrics beyond those used in Badger, et al. that can be used in answering when it is safe for rotator cuff repair patients to return-to-drive. With the limited differences observed as a function of study timepoint and sling use, it is recommended that patients are able to safely return-to-drive at two weeks post-operation. If anything, results suggest that overcompensation, as inferred from observation of safer driving behaviors than normal, is present during some experimental timepoints, particularly post-operative week 2.

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ABSTRACT GENERAL AUDIENCE

Current recommendations based on when it is safe for rotator cuff repair patients to return-to-drive are not standard because of a lack of suitable evidence. Previous work and recommendations rely on surveys and simulators which do not create fully realistic conditions and are subject to biases. To address the limitations of previous work, Badger et. al (2022) studied actual rotator cuff repair patients on public roads prior and following operation at multiple timepoints. Badger et al., however, did not consider the potential adaptations in driver behavior due to mobility restrictions and the perception of inferiority due to injury. Additionally, the degree of success of the adaptive driving behaviors based on the error between the actual vehicle path taken and a defined ideal path have not been explored in conjunction with the injury.

This investigation is based on the pre-existing data collected by the Virginia Tech Transportation Institute (VTTI) and Carilion Clinic as used in the analysis performed by Badger et al. (2022). RCR patients (n=27) executed identical driving maneuvers and drove the same route before operation and at 2-, 4-, 6-, and 12-weeks post operation. Behavioral observations were recorded and related to relevant vehicle sensor readings. To construct vehicle paths, data was taken from the on-board data acquisition system (DAS).

Participants adopted different behaviors, such as using the right hand to use the turn signal when the left arm was in a sling and the left hand to operate the gear shifter when the right arm was on

a sling, to assist in combating mobility restrictions. One-handed steering was also more prominent during periods of sling-use. Sling-use, however, did not produce a significant difference in error between the actual vehicle path taken and the ideal path available to the driver. For left-operated participants completing left turns, there was also greater error in comparison to the ideal path than for the group of right-operated patients. However, there was not a difference between left- and right-operated arm participant error in completion of a right turn. The GPS data did not provide a suitable approximation of vehicle trajectory.

Overall, findings from this study help to answer when it is safe for rotator cuff repair patients to return-to-drive through evaluation of the effectiveness of compensatory behaviors adopted by participants. With no significant difference in turn execution based on sling use, results suggest that patients can safely return-to-drive at two weeks post-operation. In fact, results suggest that overcompensation towards safer behaviors is present during some experimental timepoints, particularly post-operative week 2.

Dedicated to my mother. Continue to be strong and be a light in this world.

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Chapter 1- Introduction

With more than 2 million Americans experiencing a form of rotator cuff issue annually, there is disproportionately scarce research relating driving and rotator cuff injury (Cleveland Clinic, n.d.). The rotator cuff is a part of the shoulder joint and consists of tendons and muscles. The four major muscles of the shoulders are the subscapularis, the supraspinatus, the infraspinatus, and the teres minor—which encapsulate the head of the humerus bone (Brand, 2008; OrthoInfo, 2010). Each muscle of the shoulder joint has a function which helps facilitate the shoulder range-of-motion, which must inherently balance against the stability of the joint (Veeger & van der Helm, 2007). However, a supraspinatus tear is the most common rotator cuff tear. The supraspinatus is responsible for aiding the stability of the joint as well as the abduction of the humerus (Jeno et al., 2022). The subscapularis is the largest and strongest muscle of the rotator cuff with a mainly contributing to internal rotation (Aguirre et al., 2022). In contrast, the infraspinatus is responsible for external rotation and lateral rotation of the humerus (Williams et al., 2022). The teres minor aids in the external rotation of the arm with respect to the shoulder (Juneja & Hubbard, 2022). Tear to such a joint due to a loss of stability, therefore, can have major impacts in mobility and adversely affect many everyday actions such as driving.

Surgery is used as a treatment method for rotator cuff tear and joint instability which poses a different set of challenges for patients and raises new questions such as when it is safe for patients to return to drive. Current return-to-drive recommendations for patients following rotator cuff repair (RCR) surgery are not uniform due to a lack of empirical evidence relating driving safety and time-after-surgery. Since driving is an essential need in many areas of the country poorly served by public transportation, rotator cuff repair surgery patients often experience burdens from their postoperative restrictions or simply violate them.

Medical Conditions and Driving: A Review of the Scientific Literature (1960 - 2000) (Dobbs, 2005) posits a rationale that, while not fully investigated, medical conditions can contribute to motor vehicle crashes. Motor functioning issues and corresponding potential driving safety concerns are mentioned in Dobbs (2005); however, rotator cuff repair and driving are not explicitly mentioned. Additionally, existing driver fitness medical guidelines do not include recommendations for return-to-drive following rotator cuff repair, although other temporary impairment conditions and surgeries are featured in such guidelines (Driver Fitness Medical Guidelines, 2009). The closest guideline featured in the *Driver Fitness Medical Guidelines* (2009) does not allow for a clear recommendation due to lack of conclusive evidence but states "individuals with upper-extremity casts should delay driving resumption until the cast is removed if a large portion of the arm and/or the thumb is immobilized" as a guidance statement. Once again, this further highlights the lack of empirical evidence in terms of formulating a conclusive recommendation. This guideline may be surrogated for the potential of return-to-drive after the removal of the sling as the immobilizer but is not specific to shoulder surgery or supported as a clear recommendation through compelling research (Driver Fitness Medical Guidelines, 2009). Following anterior cruciate ligament (ACL) surgery, another temporal impairment, individuals are able to return-to-drive 4 to 6 weeks following operation (Driver Fitness Medical Guidelines, 2009). In addition, impairment levels and mobility restrictions associated with the rotator cuff tear ***prior to*** surgical intervention are often neglected in research and are not considered in guidelines.

Previous work investigating the impact of rotator cuff repair on driving has depended primarily on surveys and driving simulators. Lack of a definitive standard for return-to-driving recommendations for surgery patients, however, results in wide variations in physician recommendations, with many following conservative guidelines. Motivated by this, Gholson et al. investigated the patient experience and perception of return-to-drive recommendations following rotator cuff repair through patient surveys. Results indicated that patients returned to driving within a period ranging from the day of the surgery to four months after the surgery (Gholson et al., 2015). This large range indicates the extreme variations among return to drive following the operation. While surveys allow large amounts of data to be gathered rather quickly and at a low cost, this is a self-reported rather than an empirical measure. Studies indicating that most drivers perceive their own abilities to be better than those of others demonstrate a lack of self-awareness, a crucial limitation of surveys.

In contrast, Hasan et al. examined the impact of shoulder immobilization with a sling on a cohort of 21 healthy subjects in a simulator (Hasan et al., 2015). Driving fitness was evaluated based on performance parameters such as collisions and lane deviation over the centerline and off the road. Results showed that shoulder immobilization increased the total number of collisions from a total of 36 collisions in the no-sling state to 73 in the sling state. The use of healthy subjects, however, ignores the potential presence of compensatory behavior adopted by individuals to manage pain and mobility restrictions from the tear to the rotator cuff itself. In part to address this limitation, a subsequent study by Hasan et al. (2016) examined rotator cuff repair patients pre-operatively and at timepoints two, six, and twelve weeks post-operatively in a driving simulator. The same parameters as the previous study were used to evaluate driving fitness.

Results indicated that patients returned to pre-operative driving levels at six weeks post-surgery, although the best driving performance was observed at twelve weeks post-surgery. Driving simulators, however, lack complete fidelity to the driving task, have not been extensively validated, and can be uncomfortable (de Winter et al., 2012). Therefore, understanding the experience of these patients while driving on public roads may provide more valid findings than previous simulator research.

To address the limitations of previous work, Badger et al. (2022) evaluated the driving fitness on public roads of patients prior to rotator cuff repair and at weeks 2,4,6, and 12 following surgery. The goal of the study was to make evidence-based recommendations in an environment with higher fidelity than that of a simulator and not subject to biases inherent to surveys. Kinematic metrics such as speed, longitudinal acceleration, lateral acceleration, yaw, and jerk were used to assess driving fitness. With the pre-operative drive considered as baseline, non-inferiority in subsequent post-operative drives was observed through a series of pre-determined driving maneuvers. Badger, et al. concluded that RCR patients can return to driving as early as 2 weeks following rotator cuff repair. While the primary outcome from the study was the publication of evidence-based return-to-drive recommendations mainly based on kinematic metrics, it is possible to also examine secondary outcomes during the drives, such as observed compensatory techniques and the quantification of maneuver "success" based on ideal path comparison. These examinations will be complementary to the initial effort and form the basis of this study.

Chapter 2- Literature Review

2.1 Driver Behavior

The concept of adaptive behavior due to perceived impairment is not exclusive to return-to-drive applications. As explored in psychology, for example, a self-fulfilling prophecy is the concept that a thought or expectation comes to fruition due to resulting behaviors aligning to confirm the belief (Virginia Department of Health, n.d.). Additionally, the placebo effect demonstrates that a beneficial result can be produced from the belief in a treatment rather than the physical properties of the treatment itself (National Center for Complementary and Integrative Health, n.d.). Applying theories such as these to the realm of driving post-surgery, patients may overestimate or continually perceive their state of impairment from the surgical intervention. For RCR specifically, depending on the size of the tear, recovery time varies. However, it takes up to eight weeks for the tendon to heal to the bone, and almost all other post-operative restrictions are removed at week 12 (MacGillvray, n.d.). Therefore, perceived impairment may exist at any timepoint prior to 12 weeks post-operation. During this period, it is thus reasonable to hypothesize that patients may use compensatory techniques and modify vehicle operation behaviors to cope with the pain and mobility restrictions that result from their condition or associated corrective surgery, and/or their perception of these elements.

As mentioned previously, kinematic metrics can serve as a basis of assessment for characterizing driving and driver behavior, and potentially assess patient adaptations to perceived or actual impairment. For example, acceleration and resulting jerk may demonstrate the "aggressiveness" of a driver on a specific maneuver. To characterize and quantify these effects, Thompson Orfield et al. (2020) observed driving on public roads for subjects experiencing simulated post-operative wide-awake, local-anesthetic, no-tourniquet (WALANT) hand surgery limitations (e.g., bandaging, sedation). The study results suggested no detrimental effects of the post-surgery limitations on driving, and even moderate improvement in driving under the post-surgery WALANT state. The improvement was specifically observed through smoother steering and harder braking during the post-surgery WALANT state, indicating patients drove more cautiously when under the impression of impairment. The same analysis approach was used in Badger et al. (2022).

More generally, studies have assessed these types of driver compensation when engaging in risky behaviors. For example, with safety margins defined by speed, headway, and lane of travel characteristics, a naturalistic driving investigation found that safety margins were not increased with cell phone use for passenger and commercial motor vehicles (Fitch et al., 2014). The lack of compensatory behavior in this situation, however, may be due to cell phone task familiarity and the related ability to dismiss the associated "impairment" (i.e., the ensuing distraction) during the dynamic driving task. As previously alluded, best driving practices may serve as a source of compensation when impairment is perceived.

The Badger et al. study does not fully investigate the driving practices exhibited by subjects, overlooking the potential presence of compensatory behavior through observation of direct driving techniques (i.e., steering) and driving practices. Further investigation into such driver behavior and differences over time can specifically answer how drivers may modify their behaviors to address a perceived state of impairment. Overall, the previous literature and the functional limitations placed on patients by RCR surgery suggested five behaviors that may indicate compensatory techniques by RCR patients. These behaviors will be assessed in terms of frequency and associated characteristics in the proposed behavioral analysis: (1) use of vehicle controls ipsilateral to the operative extremity, (2) performance of non-primary tasks, (3) behavioral adjustment when traversing rough terrain, (4) steering techniques used, and (5) approaches used to visually check surroundings. Each of these behaviors is discussed in more detail below.

2.1.1 Use of Ipsilateral Controls

Ipsilateral vehicle controls refer to those that are on the same side of the body to the operative extremity (Oxford languages, n.d.). Ipsilateral control manipulation serves as an investigation of interest in this work due to patient movement restrictions associated with sling use. There are two vehicle controls that will be leveraged for this assessment given their frequent use and locations on opposite sides of the driver: turn signal levels and the vehicle gear shifter.

Turn signal levers are typically located to the left of the steering wheel and represent a standard technology whose use is legally required by vehicle operators (SAE, 2012). Turn signals provide a means to externally communicate indicated path of travel and reduce crashes. The turn signals are typically activated by the left hand to avoid a state of arms crossed in front of the steering column. Sullivan et al. (2015) determined that situational factors determined turn signal usage with 25% of left turns unsigned and 29% of right turns unsigned. With compliance measured through percentages, turn signal use provides insight into safety considerations and conservativeness of vehicle operators.

In addition, vehicles contain shifters on the right side of the vehicle that adjust the motion of vehicle through the state of the transmission. Manual vehicles have gearshift have gears for park (P), reverse (R), neutral (N), and drive (D). Gear shifting is a primary vehicle function as it directly relates to the motion of the vehicle. Similar to turn signals, the shifter is typically manipulated by the ipsilateral hand due to proximity to the function and to avoid a state of arms crossed in front of the steering column.

2.1.2 Performance of non-primary tasks

For the purpose of this analysis, non-primary tasks are defined as those not essential to proper vehicle operation. Examples of non-primary vehicle tasks under this definition include controlling the audio output, manipulating climate controls, opening and closing the sunroof, and manipulating the vehicle visor. These non-primary tasks are commonplace in driving but raise concerns regarding distractions from the dynamic driving task. It is important to remain attentive during the performance of these tasks as crash risk doubles when looking away from the road for greater than two seconds (Dingus, 2020). With mobility restrictions and potential adaptations to steering practices, greater coordination for the performance of non-primary tasks must be carried out by the driver and will be assessed in the proposed study.

2.1.3 Traversing Rough Terrain

Road smoothness is considered a target in the development of roads as a metric in increasing ride quality (Federal Highway Administration, n.d.). Vehicle suspension systems also mitigate vibrations due to rough terrain traversals, reducing relative motion between the driver and the vehicle. Rough terrain impacts longitudinal accelerations, lateral accelerations, speed (which is typically decreased), and vertical accelerations. Jerk is an acceleration-derived parameter which can aid in classification of the smoothness of the passenger experience. Jerk is defined as follows:

$$J = \frac{da(t)}{dt} \tag{1}$$

Jerk, therefore, is quantified as the time (t) rate of change of acceleration (a). Overall, rough terrains create movement in the vehicle cabins which may cause undesirable, unexpected, and forceful passenger contact with the vehicle interior. With a sensitive upper extremity, avoidance of cabin contact and a more ideal, smoother passenger experience may be sought by patients through behavioral adaptations, which indicates the reasoning for selection of this element for additional analysis.

2.1.4 Steering Techniques

Steering of the vehicle is directly related to the movement and can be maximized for vehicle control. According to the National Highway Traffic Safety Administration (NHTSA), deficient steering techniques are attributed as the leading cause of run off road crashes (NHTSA, n.d.). Steering techniques are continually evolving, with modern technology outdating classical practices. NHTSA defines three distinct steering approaches: hand-to-hand, hand-over-hand, and one hand steering in the "Using Efficient Steering Techniques" guide. The hand-to-hand steering method is the recommended method. Hand placement for both Hand-to-Hand and Hand-over-Hand is with the left hand between 7 and 8 o'clock and the right hand between 4 and 5 o'clock. One hand steering is the recommended steering practice when reversing the vehicle or operating vehicle controls. According to the guide, "when the driver is required to reach for an operating control, it is important to keep the other hand in the normal vehicle operating position of 8-9 o'clock or 3-4 o'clock, depending on steering wheel design. This keeps vehicle stability, reduces steering reversals, and allows for additional steering efforts as needed" (NHTSA, n.d.).

Despite these recommendations for two-handed steering, Walton and Thomas (2005) found that one-handed driving occurred in 50% of naturalistic observations they performed. Therefore, while levels of one-handed driving may be elevated due to mobility and pain restrictions present for RCTR, this steering technique is already highly prevalent in the general population. Nevertheless, adaptations to steering techniques associated with pre- and post-operative restrictions must be considered due to their impact to vehicle control and will therefore be examined in this investigation.

2.1.5 Approaches Used to Visually Check Surroundings

Intersections and interactions between vehicles create circumstances where conflict, and consequently crashes, can occur between vehicles (Federal Highway Administration, n.d.). Unsignalized intersections, such as yields, require the driver to be aware of surrounding vehicles as the driver may proceed so long as other road users are not present. In the case of other road user presence, the vehicle must come to a stop and proceed as safe to do so (Drivers Ed, n.d.). A specific type of yield is referred to as merging, which typically requires switching travel lanes. To safely and effectively navigate these types of maneuvers, drivers must be able to visually check their surroundings. Gattis and Low (1997) discuss driver difficulties in navigating skewed intersections, that is, intersections where the angles of the crossing streets heavily deviate from the desired 90 degrees. One such difficulty described regarding skewed intersections is that "drivers with certain physical limitations may find it more difficult to turn their head, necks, or upper bodies in order to have adequate line-of-sight down an acute angle approach" (Gattis and Low, 1997). Therefore, the impact of physical limitations that RCR patients may experience will be analyzed in this investigation by determining whether drivers are looking over the shoulder in acute intersections following RCR, along with other potentially compensatory methods used to navigate yield maneuvers.

2.2 Vehicle Dynamics and Trajectories

The aforementioned compensatory techniques may result in apparent success as driving maneuvers are successfully completed, but the degree to which those maneuvers match the ideal vehicle trajectories is unknown. Vehicle trajectories typically track the position of a vehicle in space. With one goal of automation being to have the vehicle be somewhat or completely independent in maneuvering to reduce human input and error, autonomous vehicle algorithms may serve as a basis in determining the ideal trajectory. Actual vehicle trajectories may be determined through vehicle dynamic models, however, parameters required by these models often depend on costly instrumentation. A proposed alternative to these models is to use standard and readily available global positioning (GPS) data from the vehicle to potentially predict similar characteristic patterns and error profiles to the actual vehicle path. This section describes previous work to develop approaches to determine an ideal vehicle path and methods to assess how closely an actual path resembles such an ideal path as a function of the available sensors.

2.2.1 Ideal Path Definition

Four components factor into decision making for autonomous vehicles: route planning, behavioral layer, motion planning, and local feedback control. The motion planning component of autonomous vehicles directly corresponds to finding a suitable trajectory and drives the determination of the ideal path. In path planning, feasible and optimal paths are considered. For the creation of the ideal path, a constraint-aware optimal path based is typically used (Paden et al., 2016). For on-road planning, Ferguson et al. (2008) proposes planning the vehicle path based on the centerline of the target lane. Additionally, velocity is constrained based on the behavioral layer by the speed limits of the road. The alignment of ideal trajectories based on lane positioning aligns with goals of other automated features, for example, lane centering (SAE, 2021). The lane centering feature detects lane boundaries, and, as the name implies, keeps the vehicle centered along the path (Bosch, n.d.). Therefore, for the purpose of this analysis, the ideal path is defined to be that in which the vehicle remains centered in the desired lane of travel.

The design of infrastructure and roadway planning also aid in the definition and understanding of the ideal path taken by a vehicle. The swept path, for example, is the amount of space that a vehicle requires to safely complete a turn (Queensland Government, n.d.). By simulating a variety of vehicles, proper lane spacing, turn angles, and, overall, roadway planning may be improved. Typically, a standard lane has a width of 10 feet with cost-benefits determining the need for widening on specified roadways (Ink, 2015). Once again, the swept path demonstrates the importance of spatial awareness in lane navigation. Roadway planning also incorporates speed limits into this determination based on potential conditions and vehicles. In general, however, these considerations do not preclude the use of lane centering as a key criterion in ideal vehicle path assessment.

2.2.2 Actual Vehicle Path Determination

Actual vehicle path tracking can be determined from the vehicle parameters via geometric, kinematic, and dynamic models (Snider, 2009). Vehicle parameters can be determined from physical characteristics of the modeled system as well as kinematic metrics acquired from data acquisition systems. However, acquisition of such information is relatively difficult.

A common and relatively simple kinematic model is known as the bicycle model. In this model, the front tires and rear tires are combined, reducing the degrees of freedom within the system. The kinematic bicycle model is accepted and used in motion planning at a low level. The model is believed to capture enough of the defining characteristics of a true vehicle system (Polack et al. 2017). This will be the model used throughout this analysis to represent the actual path taken by the vehicle. Actual position of the vehicle can be determined through continuous computation as information becomes available from available vehicle data.

The bicycle model is based on three governing equations in relation to the center of the rear axle (Barzegar et al., 2021):

$$\dot{\varphi} = \frac{V}{L}\sin(\delta) \tag{2}$$

$$\dot{X} = Vcos(\varphi) \tag{3}$$

$$\dot{Y} = Vsin(\varphi) \tag{4}$$

In the equations, φ represents the heading angle. The rate of change of the heading ratio is based on the vehicle velocity (V), steering angle (δ) and distance between the wheel axles (L). The $\dot{X}$ and $\dot{Y}$ represent the rate of change of X and Y position with respect to time, respectively.

2.2.3 Standard GPS Path

As previously mentioned, vehicle parameter models require information from complex instrumentation that can be expensive and difficult to collect. With the widespread use of GPS and the low cost of such systems, however, using GPS for the determination of vehicle path could present immense benefits (Preda et al., 2009). Much of the current use for GPS data is based on tracking vehicle position (Zein et al., 2017) or routes taken (Xu et al., 2021). However, Preda et al. describe introductory methodology for connecting GPS data to vehicle dynamics. In that application, information obtained from GPS readings was transformed into local coordinates. Vehicle trajectory was found using a circle connecting three points (past, current, and future), and a straight-line approximation used in instances where the circle radius approached infinity. Methods such as these rely heavily on the accuracy and resolution of the instrument; with lower resolution information, the degree to which the GPS models can accurately describe the vehicle path is unknown. In a study comparing the fusion of GPS, inertial navigation system (INS), and odometer readings, the maximum GPS error produced an error in position of 0.15 meters (Aftatah et al., 2016). Therefore, the GPS path represents an approximation of the vehicle path which may be further evaluated in terms of effectiveness in describing vehicle behavior. Typically, for trajectory analysis, the average displacement error and final displacement error are used as the primary performance metrics (Rossi et al., 2021). These metrics are also useful in path evaluation.

2.3 Research Questions

Currently, gaps in knowledge regarding return-to-drive following arthroscopic rotator cuff repair exist. Specifically, compensatory driving behaviors developed prior to and following the surgery, and quantification of maneuver "success" based on ideal path comparison, are not considered in the literature. The proposed study, therefore, aims to address these gaps through investigation to address the development and evaluation of the following research questions. The first two research questions are focused on driver behavior and divided based on mobility restrictions (question 1) and perceived impairment (question 2). The remaining research questions are focused on the vehicle trajectory models and are focused on maneuver success (question 3) and model accuracy (question 4). Operable definitions of terms fundamental to the research questions may be found in Table 1.

Table 1: Summary of Research Question Terms and Definitions

Term	**Definition**
Driver Behavior	
Mobility Restrictions	Whether the operative extremity is restricted by a sling
Ipsilateral	That on the same side of the operative extremity (i.e., turn signal for left corrective operation and gear shift for right corrective operation)
Difficulty	Indicates one of the following conditions were met: • Force: Insufficient force to activate the control on an attempt • Slip: Hand slips from control during operation • Control: Losing control of the wheel during control operation/Need to reposition during control attempt • Directionality: Inability to place control in the correct direction
Non-primary Task	A task that is not directly related to the dynamic driving task
Fluid Motion	Completion of task in a continuous motion without interruption
Perceived Impairment	The level at which an individual believes they have a decreased ability. For this study, perceived impairment is evaluated at drives prior to week 12 post-operation.

Vehicle Trajectory	
Ideal Path	Hypothetical path in which vehicle remains centered in the desired lane of travel
Actual Vehicle Path	Path determined from standard kinematic bicycle model based on vehicle kinematic data
Standard GPS Path	Path determined from GPS coordinates, connecting sequential GPS points (“breadcrumbs”) through approximation

The research questions of the study are as follows:

1. **Do drivers compensate for mobility restrictions associated with upper extremity corrective operation?**
   a. Are there modifications in control of ipsilateral vehicle functions when mobility is restricted from sling use?
      i. Hypothesis 1a-i: There will be an increase in the number of drivers that use the non-ipsilateral hand to control the vehicle functions when the operative extremity is restricted from the sling.
      ii. Hypothesis 1a-ii: The number of drivers having trouble in control of ipsilateral vehicle functions will increase during states of sling use. For turn signal use, the greatest difficulty will be due to the hand not fully grasping, and therefore slipping, from the signal. In gear shifting, the greatest difficulty will be due to insufficient force to move the shifter to the correct gear for the maneuver.
   b. Are drivers able to perform non-primary vehicle tasks when mobility restrictions are present?
      i. Hypothesis 1b-i: Drivers will need more time to prepare for non-primary tasks while in a sling, but the amount of time required to complete the

dynamic task itself will decrease with sling use. Most drivers will not have the operative extremity on the wheel prior to instruction to complete non-primary tasks.

ii. Hypothesis 1b-ii: The number of drivers able to complete non-primary tasks in a fluid motion will decrease with sling use.

iii. Hypothesis 1b-iii: Most drivers will use the non-operative extremity hand to interact with and complete the non-primary vehicle task with the operative extremity on the wheel during periods of sling use.

c. Do drivers adapt steering techniques used to perform driving maneuvers while using a sling?

i. Hypothesis 1c: The amount of one-handed steering will be greater during periods of sling use.

2. Do drivers exhibit changes in behavior when impairment is perceived?

a. How do drivers modify vehicle behavior when traversing rough terrains, such as train tracks?

i. Hypothesis 2a-i: Kinematic metrics such as jerk and range of acceleration will decrease during drives prior to 12 weeks post-operation.

ii. Hypothesis 2a-ii: Drivers will modify body behavior to avoid contact with the vehicle interior cabin during the drives prior to 12 weeks post-operation.

b. Do driver approaches to visually check surroundings change during periods of perceived impairment?

i. Hypothesis 2b-i: Drivers will decrease looking over the shoulder during drives prior to 12 weeks post-operation.

ii. Hypothesis 2b-ii: Drivers will increase leaning forward during yield and merge maneuvers to increase the field of view and counteract decreased over-the-shoulder checks during drives prior to 12 weeks post-operation.

3. To what degree are drivers able to successfully complete maneuvers following rotator cuff corrective surgery?

a. Do mobility restrictions from sling use impact the completion of the ideal maneuver?

i. Hypothesis 3a: Final displacement error and average displacement error will be greater for drives completed in a sling than those completed without a sling as measured through the comparison of actual vehicle path to the ideal path.

b. Are there impacts on the successful completion of maneuvers ipsilateral to the operative extremity?

i. Hypothesis 3b: Final displacement error and average displacement error will be greater for maneuvers ipsilateral to the operative extremity as measured through the comparison of actual vehicle path to the ideal path.

4. How accurate is path estimation derived from standard GPS coordinates compared to the actual path taken by the vehicle (as determined based on metrics from a data acquisition system and a vehicle parameter model)?

a. Is the GPS model able to describe the same vehicle behavior as the vehicle data-driven parameter model?

i. Hypothesis 4a: The GPS model will have a suitable displacement error (within 0.15 meters) from the actual vehicle path.

b. Do both the GPS model and the vehicle data-driven parameter model lead to the same result patterns?

ii. Hypothesis 4b: The GPS model will have a similar error profile compared to the ideal path than the error profile between the actual path and ideal path.

Chapter 3-Methods

To address the research questions of interest, this investigation uses the pre-existing data set collected by the Virginia Tech Transportation Institute (VTTI) and Carilion Clinic as used in the analysis performed by Badger et al. (2022). This data set contains multidimensional, longitudinal data collected from rotator cuff repair patients performing prescribed driving maneuvers on public roads. The subjects executed the same maneuvers in a preoperative state as well as 2,4,6, and 12 weeks post operation. For the drives at weeks 2 and 4 post-operation, the participants were instructed to properly wear their prescribed sling, securing the operative extremity. All driving tests were completed along a 15-mile (approximately 45 minute) study route in Roanoke, Virginia that contained a mix of residential areas, city roads, highways, and parking maneuvers, as shown in Figure 1**.** Drives were completed under the supervision of a trained driving experimenter who provided oral instructions and directions to participants and served as a safety monitor. Participants were asked to obey all traffic laws, use turn signals at turns and prior to lane changes, and adhere to posted speed limits.

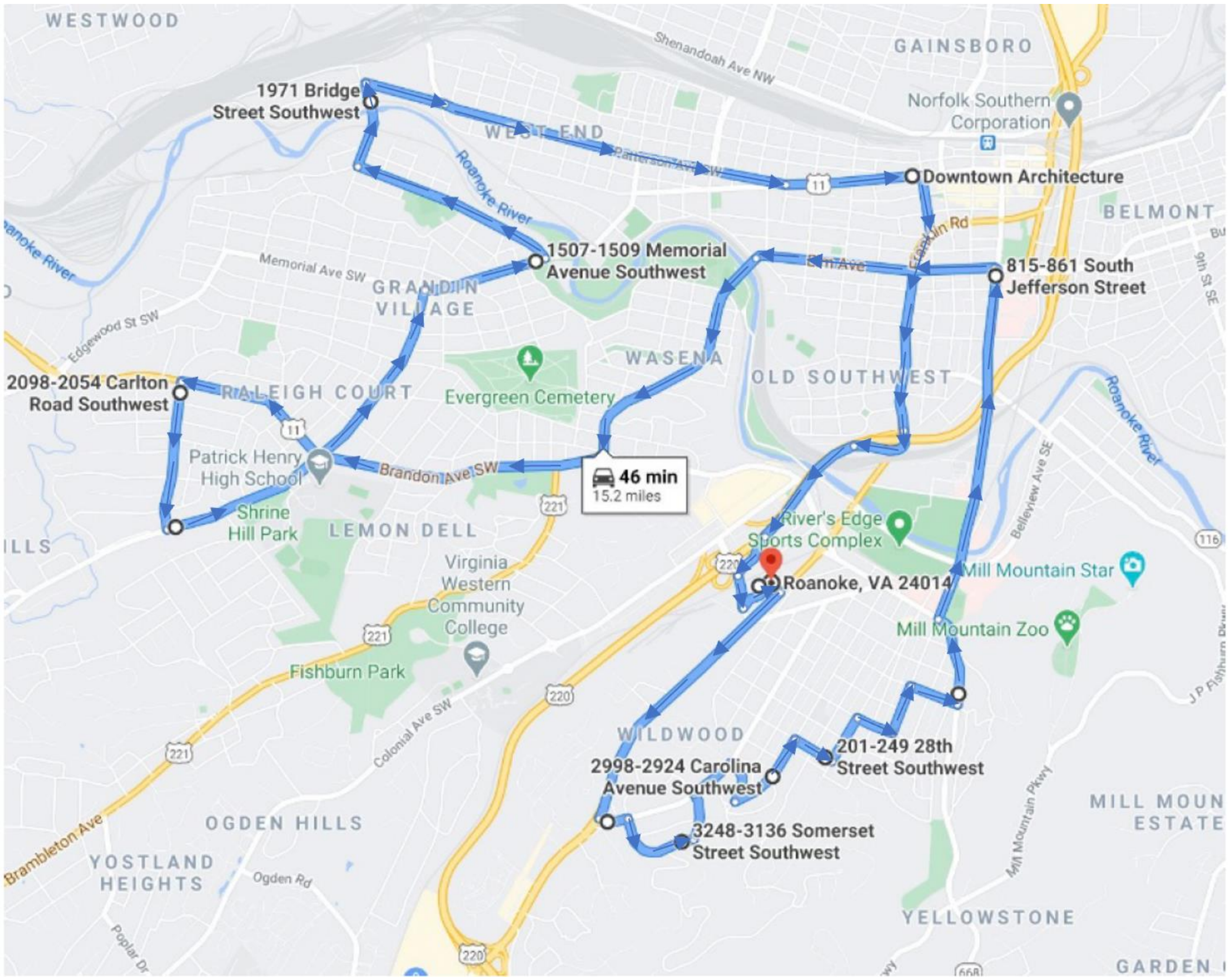

Figure 1: Map of Route Used in Experiment

3.1 Participants

Thirty-two participants between the ages of 43-68 (average age 58.6) were enrolled in the study with 27 subjects completing all five drives for the study. Of the 27 participants completing all the drives, 14 participants had rotator cuff repair on their left shoulder while the remaining 13 participants had the surgery on their right shoulder. Requirements for patient participation included: (1) undergoing primary RCR, (2) possessing no other medical condition that impairs driving, (3) aged 40-69 years old, (4) the ability to drive independently at baseline (pre-operatively), (5) postoperative instructions that require the use of a sling until week 6, (6) possessing a valid driver's license, and (7) anticipated discontinuation of sling at postoperative week 6. Enrollment excluded patients under the influence of drugs impairing reaction time and those with concomitant procedures. These concomitant procedures excluded subacromial decompression, biceps tenodesis, biceps tenotomy, distal clavicle excision, and extensive debridement. Extensive debridement was defined by the research team based on Current Procedural Terminology (CPT) code 29827 as "debridement of ≥3 discrete structures (e.g., humeral bone, humeral articular cartilage, glenoid bone, glenoid articular cartilage, biceps tendon, biceps anchor complex, labrum, articular capsule, articular side of the rotator cuff, bursal side of the rotator cuff, subacromial bursa, foreign body[ies])" (Badger et al., 2022). Participants were not selected randomly to provide a representative sample based on sex and age.

3.2 Vehicle

An instrumented 2015 Infinity Q50S was the research vehicle used for data collection. The vehicle was instrumented with a VTTI data acquisition system (DAS) where video of each drive was recorded with views of: (1) the driver's face, (2) over-the-shoulder, (3) the rear and front of the vehicle, and (4) the driver's foot as shown in Figure 2. The DAS was also equipped with sensors transmitting information about the vehicle such as headlight use, turn signal use, and vehicle acceleration to be used for analysis. Additionally, the vehicle contained a rear steering wheel and brake to be used by the driving researcher to partially control the vehicle in case of an unexpected safety critical event.

Figure 2: Camera Views Collected

3.3 Maneuvers of Interest

Maneuvers of interest were defined throughout each of the prescribed drives to allow observation of the same situation for each participant during each drive. These maneuvers were determined by the research team, considering anticipated driving events of interest, and defined based on either spatial landmarks along the route or by actions taken by the participant. Data visualization software was used to view the videos and isolate the maneuvers based on the timestamps of occurrence. An initial video capturing study personnel driving the route was used to identify landmarks and actions that defined the maneuvers, and as a reference for the maneuver definition protocol (**Appendix A)**.

For the behavioral portion of the study, sixteen distinct maneuvers of interest throughout the drive were defined. The breakdown of these maneuver types is shown in Table 2. Each of the sixteen maneuvers selected specifically aligns with at least one the five behavioral domains established and previously introduced (i.e., use of ipsilateral controls to operative extremity, performance of non-primary tasks, traversing rough terrain, steering techniques, and approaches used to visually check surroundings). The maneuvers were distributed, to the extent possible, throughout the duration of the drive. The location of each of the behavioral maneuvers, excluding the parking lot maneuvers, may be seen in Figure 3. **Appendix A** specifies the directions given to the participant for each maneuver, comments regarding maneuver selection, the beginning and end of the maneuver, and provides visual aids, as necessary.

Table 2: Breakdown of Behavioral Maneuver Types

Maneuver Type	Maneuver Name	Behavior(s) Captured
Parking Lot	M1: Reverse	• Use of Ipsilateral Controls (Right Side- Gear Shifting)
	M2: U-turn	• Steering Techniques Used
	M3: Parallel Parking	• Use of Ipsilateral Controls (Right Side- Gear Shifting)
	M4: Roundabout	• Steering Techniques Used
Left Turn	M5: Carolina Left	• Steering Techniques Used
	M6: Crystal Left	• Steering Techniques Used • Use of Ipsilateral Controls (Left Side- Turn Signal Use)
	M7: Yellow Left	• Steering Techniques Used • Use of Ipsilateral Controls (Left Side- Turn Signal Use)
Straightaway	M8: Straightaway	• Steering Techniques Used
Visor	M10: Visor	• Performance of Non-primary Tasks
Train Tracks	M11: Train Tracks	• Traversing Rough Terrain
Right Turn	M12: Patterson Right	• Steering Techniques Used
	M14: Franklin Right	• Steering Techniques Used • Use of Ipsilateral Controls (Left Side- Turn Signal Use)
Yield	M9: Brandon Yield	• Approaches Used to Visually Check Surroundings
	M13: Yield	• Approaches Used to Visually Check Surroundings
Lane Change	M15: Merge Left	• Approaches Used to Visually Check Surroundings • Use of Ipsilateral Controls (Left Side- Turn Signal Use)
	M16: Merge Right	• Approaches Used to Visually Check Surroundings

		• Use of Ipsilateral Controls (Left Side- Turn Signal Use)
Total	**16**	

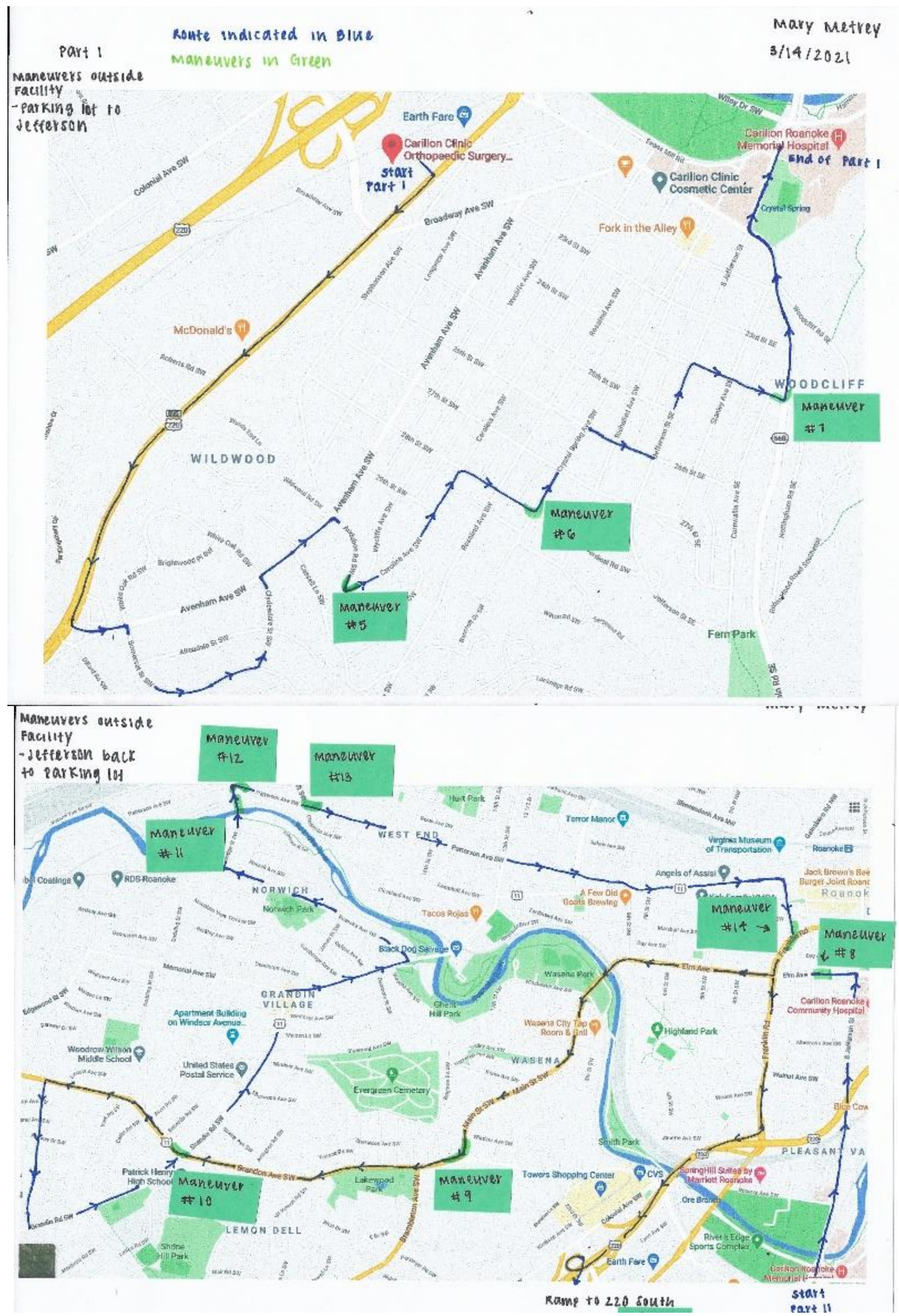

Figure 3: Distribution of Maneuvers Along Route

Four maneuvers of interest were selected to be used for analysis of deviation from the ideal trajectory. For this analysis, maneuvers of interest were isolated solely based on distinguishable landmarks surrounding the area of the event. Specifically, a standard left turn, a standard right turn, a non-standard left turn, and a straightaway were selected to be used throughout the analysis of the study through the following process. Pre-existing defined maneuvers from the behavioral analysis were initially considered as potential trajectory maneuvers as well. The behavioral maneuvers, however, did not completely align with the goals of the trajectory analysis. Therefore, new distinct driving events were selected to fulfil the requirements of the standard left and right turn maneuvers. The full discussion and selection of the maneuvers for the trajectory analysis may be found in **Appendix B**, and the maneuver definitions for the trajectory specific maneuvers may be found in **Appendix C**.

3.4 Behavioral Data Reduction

Behavioral data reduction served as the mechanism for defining key characteristics of the behavioral maneuvers of interest. The data observation was performed using VTTI data visualization software, utilizing a mix of video and vehicle sensor readings for each drive and maneuver. Annotations regarding the operative extremity, whether the operative extremity was in a sling, and general notes regarding the drive were recorded for each drive as video annotations. The manually reduced observations were recorded using Microsoft Excel. The full protocol, used as a guide for the classification of events, is available in **Appendix D**.

The ipsilateral vehicle control analysis focused on turn signal usage (left side) and gear shifting (right side) during parking tasks. Specifically, use of the turn signal, hand used for activation, use technique, and use difficulty (e.g., multiple attempts needed to activate the signal, losing control of steering during activation) were determined. These metrics were recorded and determined from the over-the-shoulder videos of the participants and the turn signal activation time history within the vehicle data. For gear shifting, hand used, time to complete the shift, and use difficulty (e.g., initially shifting into the incorrect gear) were assessed. When required, the over-the-shoulder video of the participant allowed the time of the maneuver to be extracted based on the pre-established definitions.

Performance of non-primary vehicle tasks, or tasks that are not essential to safe vehicle operation, was examined through participant manipulation of the sun visor in the vehicle, as directed by the researcher. Hand placement on the wheel during the visor task, hand used to manipulate the visor, and time required to complete the maneuver served as the basis for analysis of this task. Once again, the timestamps of specific elements of the driver tasks and observations were recorded from the over-the-shoulder video data collected.

To study compensatory behaviors on rough terrain, a straightaway driving maneuver over train tracks was analyzed. Researchers assessed preparatory body position alteration to avoid contact with the vehicle interior along with lateral and vertical accelerations attained during the maneuver. To extrapolate these metrics, the maximum and minimum of vertical acceleration (Z-acceleration) and lateral acceleration (Y-acceleration) was taken from vehicle data. The over-the-shoulder video data was used to determine whether the body position of the participant was altered.

In addition, steering techniques on U-turns, roundabouts, straightaways, and turns were analyzed based on number of hands on the wheel. Data supporting these assessments was based on observation of the over-the-shoulder view of the participant. The position of each hand at each timepoint was associated with different positions in a clock. Options for hand not on the wheel and unknown hand placement were also recorded. This data was recorded through an annotation in the data visualization software.

Finally, the methods used by participants to examine their surroundings during yield and merge maneuvers were extracted. The participant over-the-shoulder videos were coded to determine whether a glance over the shoulder was performed, while the face video was analyzed to determine whether the participant leaned forward to increase the side mirrors field-of-view. A summary of metrics recorded, and the associated maneuvers, may be found in Table 3.

Table 3: Summary of Metrics Associated with Behavioral Domains

Behavioral Domain	**Maneuvers**	**Metrics**
1) Use of Ipsilateral Controls	Left Side: M6, M7, M14, M15, M16 Right Side: M1, M3	• Hand Used • Difficulty
2) Performance of Non-primary Tasks	M10	• Task Time • Fluid Motion • Operative Hand Prior to Task • Wheel Hand • Visor Hand
3) Traversing Rough Terrain	M11	• Longitudinal/Latitudinal Acceleration Range • Longitudinal/Latitudinal Jerk • Contact Avoidance
4) Steering Techniques Used	M2, M4, M5, M6, M7, M8, M12, M14	• Hand Position
5) Approaches to Visually Check Surroundings	M9, M13, M15, M16	• Look Over Shoulder • Lean Forward

3.5 Behavioral Analysis

Behavioral observations were made in Microsoft Excel. For categorical variables, the data was collapsed using pivot tables. The condensed data tables were then individually processed using JMP Pro 16 software. A chi-square test was performed on frequency counts for all categorical behavioral observations. Similarly, the numerical variable tables were transferred from Microsoft Excel to JMP for data analysis. The numerical data were evaluated using ANOVA. A summary of the statistical models used based on the research questions and dependent variables may be found in Table 4.

Table 4: Behavioral Analysis Models

Research Question	Factor(s)	Dependent Variable(s)	Statistical Model
1.Do drivers compensate for mobility restrictions associated with upper extremity corrective operation?			
Are there modifications in control of ipsilateral vehicle functions when mobility is restricted from sling use?	- Sling use - Operative extremity	- Hand Used - Difficulty	- Chi-Square
Are drivers able to perform non-primary vehicle tasks when mobility restrictions are present?	- Sling use	- Time	- One-factor ANOVA
		- Fluid Motion - Hand Position	- Chi-Square
Do drivers adapt steering techniques used to perform driving maneuvers while using a sling?	-Sling use	-Hand Position	- Chi-Square
2.Do drivers exhibit changes in behavior when impairment is perceived?			
How do drivers modify vehicle behavior when traversing rough terrains, such as train tracks?	- Operative timepoint - Operative extremity	- Vertical/Lateral Acceleration Range - Vertical/Lateral Jerk	- One-factor ANOVA
		- Hand Position - Contact Avoidance	- Chi-Square
Do driver approaches to visually check surroundings change during periods of perceived impairment?	- Operative timepoint - Operative extremity	- Look over shoulder - Lean Forward	- Chi-Square

3.6 Trajectory Analysis Models

The identification and analysis of an ideal trajectory leveraged the mapping of an ideal path for a subset of maneuvers. This ideal trajectory was based on the position of begin and end lane centerlines during the turn and straightaway maneuvers of interest. Two methods of determining vehicle trajectory were explored, representing different levels of expected accuracy: 1) using

GPS data from the vehicle and 2) leveraging the fixed relation between the experimental vehicle kinematic measures (e.g., yaw rate, speed) and the vehicle turn radius. The comparison of measured trajectory to ideal path quantified the ability of the driver to follow a defined trajectory and was used to assess the degree of success in vehicle operation for arthroscopic rotator cuff repair patients. Calculations were made to determine the average displacement error and final displacement error for each model.

As previously introduced, the ideal path was defined as following the centerline of the vehicle lane, when such a lane existed. In instances without an explicitly defined lane, lane boundaries were determined through landmarks such as the edge of the roadway along with the curvature of the roadway. Multiple points were taken between the beginning and the end of the pre-defined maneuver (Figure 4). The points were obtained from Google Earth software and imported into MATLAB for comparison and analysis. The first point corresponded to an approximate roadway location in line with the landmark for the beginning of the maneuver. The endpoint of the maneuver was based on the landmarks' correspondence with roadway position, which was also identified within the map. Between the beginning and end of the maneuver, points were determined as changes between the x and y position detectable through the Google Earth software. The goal was to select at least one additional point with a change in longitude and one with a change of latitude for turns. Generally, more points were available from left turns than right turns since left turns tend to be longer maneuvers. For the straightaway maneuver, multiple points throughout the path were taken. Across maneuvers, all these points were scaled to meters with the origin existing at the beginning of the maneuver, identified as the first point in the sequence.

Figure 4: Sample of Waypoints in Mapping of the Ideal Turns

The kinematic bicycle model was used in the determination of the actual vehicle path. Vehicle velocity (V) and angular speed (ψ) were extracted from the on-board data acquisition system. The wheelbase of the vehicle (L) was determined to be 2.850 meters from the specifications listed for the test vehicle in the New Car Assessment Program (NCAP) (NHTSA, 2013). With the model determined, a program was generated differentiating the bicycle kinematics function in MATLAB where successive velocities and angular speeds collected for each maneuver were inputted. The initial heading was calculated based on the map data, using the first two points defining the maneuver. The model execution started at the initial maneuver point.

Longitude and latitude coordinates were directly recorded by the data acquisition system. Individual data points for these metrics were imported into MATLAB, as was done for the determination of the ideal path. These data points were then converted to meters in the same coordinate space as the ideal and bicycle model paths. The initial ideal point was arbitrarily defined as the reference zero in both the x and y directions.

With three distinct point sets generated, one for the ideal path, one for the actual vehicle trajectory (based on the bicycle model), and one based on GPS data, the average displacement error and final displacement errors were determined for the multiple possible comparisons. The pre-determined ideal points were used as the basis for comparison against the other trajectories, starting with the second ideal point (recall that the first point was used as the initial point in the bicycle model, therefore, the error for that point would always be zero). When the change between two successive ideal points was greater in the longitudinal (i.e., x) direction, the lateral (i.e., y) points of the other trajectories were interpolated to find the approximation of y at the exact x-value of interest. Error was then calculated as the distance between the points. Similarly, when the change between two successive ideal points was greater in the lateral direction, the longitudinal points of the other trajectories were interpolated to find the approximation of x at the exact point of interest. When calculating means, the absolute values of differences were generally used to prevent errors in opposite directions from cancelling each other. Instances of no corresponding points on specific trajectories for selected comparison points were rare and were removed from consideration when observed. A depiction of the path comparison approach is shown in Figure 5.

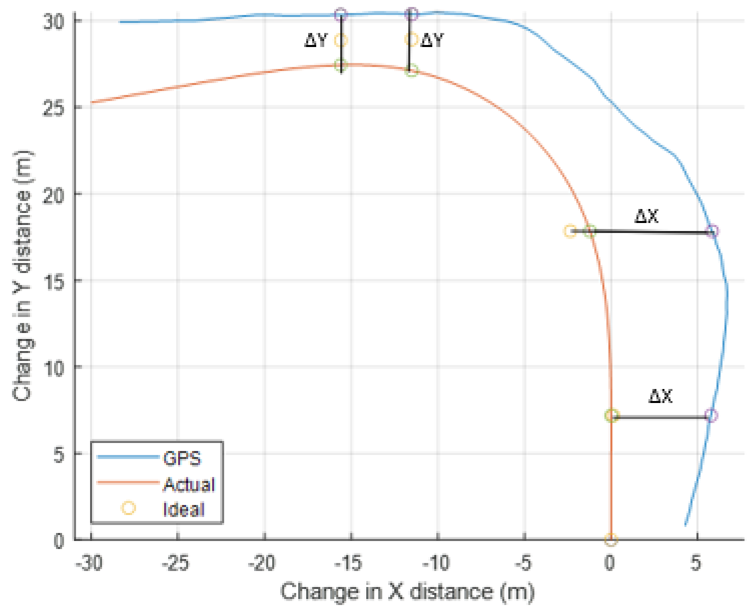

Figure 5: Comparison of Path Types

3.7 Trajectory Analysis

With the trajectory data in MATLAB, calculations were performed within the software and stored for transformation into JMP for analysis. Left and right turns were examined separately only for the ipsilateral analysis, otherwise they were aggregated. One-factor ANOVA was used in most analyses, incorporating the random effects of subject ID. A t-test was used to compare between the model types (i.e., bicycle and GPS, compared to ideal path) using a threshold maximum acceptable difference of 0.15 meters, selected based on the metrics from Aftatah et al. (2016). A summary of the pertinent research questions along with analysis approaches for the trajectory data may be found in Table 5.

Table 5: Trajectory Analysis Models

3.To what degree are drivers able to successfully complete maneuvers following rotator cuff corrective surgery?			
Do mobility restrictions from sling use impact driver the completion of the ideal maneuver?	- Sling use	- Final Displacement Error - Average Displacement Error	- One-factor ANOVA
Are there impacts on the successful completion of maneuvers ipsilateral to the operative extremity?	- Operative extremity - Maneuver type	- Final Displacement Error - Average Displacement Error	-One-factor ANOVA
4.How accurate is the data obtained from the standard GPS coordinates to the actual path taken by the vehicle as obtained through the vehicle parameters?			
Is the GPS model able to describe the same vehicle behavior as the parameter model?	- Model	- Final Displacement Error - Average Displacement Error	- T-test
Do both the GPS model and the parameter model lead to the same significant results?	- Model	- Final Displacement Error - Average Displacement Error	- One-factor ANOVA

Chapter 4-Results

A total of 27 participants completed all five drives. However, the data was missing for one participant at post-operative week 2. Data from this participant was, however, included in analyses that did not depend on this time point. Sling use across participants was variable across the experimental drives (Table 6). While the sling was prescribed to be worn until post-operative week 6, not all participants followed the physician instructions. The mean duration of sling use was 3.78 weeks (SD=1.69). A total of three participants failed to use a sling for any drive, and one participant went from no sling use back to sling use in consecutive drives. Variability in sling use further validates the importance of recording and using sling use as an observational experimental factor.

Table 6: Breakdown of Sling Use by Drive

Sling?	Drive				
	Drive 1 Pre-Operative	Drive 2 Post-Operative Week 2	Drive 3 Post-Operative Week 4	Drive 4 Post-Operative Week 6	Drive 5 Post-Operative Week 12
Yes	0	22	22	5	0
No	27	4	5	22	27

All drives were completed without the occurrence of any crashes with other vehicles. Curb strikes were rare but did occur, and the in-vehicle experimenter intervened with the rear brake during two of the drives. These interventions were necessary for different participants and during different drives—one at post-operative week 2 and the other at post-operative week 12. The intervention occurring at post-operative week 12, after the shoulder had fully healed, suggests that driver style, rather than a shoulder issue, was the likely reason resulting in the intervention.

4.1 Mobility Restrictions

4.1.1 Hand Used to Manipulate Ipsilateral Vehicle Controls

Table 7 summarizes frequencies of hand used by the participant to manipulate the turn signal during maneuvers of interest as a function of the operative extremity. Operative extremity was a significant factor ($p<0.0001$). There were 103 instances where the right hand was used to manipulate the turn signal, with all instances of such use coming from participants with a left operative extremity. In a similar manner, Table 8 summarizes the hand used to shift into an alternate gear as a function of the operative extremity. Operative extremity was also a significant factor in the hand used to manipulate the shifter ($p<0.0001$). No participants with a left extremity operation used the left hand to shift the vehicle gear, while 43 participants with a right operative extremity used the left hand on the task.

Table 7: Overall Hand Used on Left Vehicle Control Across Operative Extremity

Operative Extremity	Hand Used				
	Left	Right (Crossover)	Left/Right	None	N/A
Left	226	103	1	12	3
Right	317	**0**	**0**	3	3

Table 8: Overall Hand Used on Right Vehicle Control Across Operative Extremity

Operative Extremity	Hand Used			
	Left	Right	Left/Right	N/A
Left	**0**	119	**0**	9
Right	43	93	2	2

Further investigation into ipsilateral control use split the participants into cohorts based on operative extremity in order to assess potential effects of sling use. For the left operative extremity cohort (Table 9), sling use was a significant factor ($p<0.0001$). Participants were 16.2 times more likely to use the non-ipsilateral hand to control the turn signal when they wore a sling. The right hand was used to activate the turn signal on 80 instances when the sling was worn and 23 when the sling was not worn. Sling use was also significant for the right operative extremity cohort (Table 10; $p<0.0001$). Participants were nearly 23 times more likely to use the non-ipsilateral hand to gear shift when they wore a sling. For this right-sided vehicle function, use of the left hand occurred on 35 instances when the sling was worn compared to 8 instances when the sling was not worn.

Table 9: Hand Used on Left Vehicle Control for Patients with Left Operative Extremity Across Sling Use

Sling	Hand Used				
	Left	**Right (Crossover)**	Left/Right	None	N/A
Yes	40	**80**	0	2	3
No	186	**23**	1	10	0

Table 10: Hand Used on Right Vehicle Control for Patients with Right Operative Extremity Across Sling Use

Sling	Hand Used			
	Left (Crossover)	Right	Left/Right	N/A
Yes	**35**	15	2	0
No	**8**	78	0	2

Altogether, crossover, an instance where the non-ipsilateral hand to the vehicle function is used to manipulate the control, occurred for important vehicle functions ipsilateral to the operative extremity. Crossover is not taught or recommended due to safety implications of arms crossed in front of the steering wheel during airbag deployment. In this study, crossover occurred momentarily, demonstrating an adaptive behavior used by participants to fully operate the vehicle, particularly when they used the sling. However, at low speeds (e.g., during maneuvers in which gear shifting is required), crossover is not as dangerous as when the vehicle is in normal transit. Of particular interest is the observation that a similar behavior was adopted by multiple participants for two different vehicle functions in opposite locations. Furthermore, crossover occurred for a higher proportion of the gear shifting maneuvers compared to turn signal activation, likely due to the additional difficulty and force requirement required by gear shifting.

Additionally, crossover did not occur during periods of no sling use for vehicle functions ipsilateral to the injury. This suggests that adaptive behaviors developed from mobility restrictions may not necessarily persist after the mobility restriction is eased. In general, the sling use as a significant factor in crossover demonstrates, as hypothesized, **an increase in the number of drivers that use the non-ipsilateral hand to control the vehicle functions when the operative extremity is restricted from the sling.**

4.1.2 Difficulty with Ipsilateral Vehicle Control Functions

The cohorts of left corrective operation with turn signal use and right corrective operation with gear shifting were further investigated for any difficulty in operation of the vehicle functions (Tables 11 and 12). Sling use was not a significant determinant of difficulty (p=0.4272) for turn signal use. In such operation, 5 instances of difficulty were observed while the sling was worn compared to 13 instances when the sling was not worn. Sling use, however, was a significant factor in gear shifting difficulty (p=0.0207), increasing the likelihood of difficulty with gear shifting by 2.3 times. A total of 26 counts of difficulty were recorded for gear shifting maneuvers with and without the sling but, proportionally, difficulty was observed more often with the sling.

Table 11: Difficulty on Left Vehicle Control for Patients with Left Operative Extremity

Sling	Difficulty			
	Some	No	Unknown	N/A
Yes	5	115	0	5
No	13	197	0	10

Table 12: Difficulty on Right Vehicle Control for Patients with Right Operative Extremity

Sling	Difficulty			
	Some	No	Unknown	N/A
Yes	26	26	0	2
No	26	60	0	0

Most of the difficulty experienced by the participants operating the turn signal was due to the hand slipping from the signal during attempted activation, requiring a second attempt to activate the signal (Table 13).

Table 13: Difficulty Type on Left Vehicle Control for Patients with Left Operative Extremity

Difficulty	Difficulty Type			
	Slip	Force	Control	Directionality
Some	**13**	3	2	0

For gear shifting, the difficulty types were tabulated both across operative extremity groups and separately for right operative extremity patients (Tables 14 and 15). Across participant groups, there were 32 counts of force difficulty and 41 counts of control difficulty, with sling use found to be a significant factor for force difficulty ($p=0.0002$). Sling use, however, was not found to be a significant factor in the presence of control difficulty. Sling use was also a significant effect in the presence of control difficulty for right operative extremity patients ($p=0.0006$).

Table 14: Difficulty Type on Right Vehicle Control

Difficulty	Difficulty Type			
	Slip	**Force**	**Control**	Directionality
Some	4	**32**	**41**	25

Table 15: Difficulty Type on Right Vehicle Control for Patients with Right Operative Extremity

Difficulty	Difficulty Type			
	Slip	**Force**	Control	Directionality
Some	4	**27**	18	20

Findings only partially supported the experimental hypotheses. **Overall, the number of drivers having trouble in control of the turn signal did not significantly increase during periods of sling use while the number of drivers having difficulty with the gear shifter did increase with sling use.** This can likely be attributed to the nature of the controls. The turn signal is in a more accessible location to the driver, in that it is directly connected to the steering column. It also requires less force for activation than the gear shift. The turn signal also has a less complicated movement than the shifter. To shift gears in the experimental vehicle, the driver had to complete both a lateral and longitudinal motion, requiring fairly precise control to avoid shifting into the incorrect gear. This motion also required a larger amount of force than required for the turn signal. Implications of the difficulty observed with gear shifting are that patients should only operate vehicles with an automatic transmission during recovery, as continual difficulty with shifting could have safety implications.

In terms of the experimental hypotheses related to specific difficulty experienced, **for the turn signal, the most frequent difficulty was due to slip, but not significant as a function of sling use.** Based on the previous discussion, this is logical and aligns with expectations since not much force is required, or many movement options are available, to operate the turn signal. **In contrast, for gear shifting, the most frequent difficulty was due to insufficient force to move the shifter into the correct gear for the maneuver, which was significantly increased with sling use.** Once again, this agrees with logical expectations based on the nature of the required movement. Mobility restrictions and the corrective operation have impacts on force generation with or without the presence of a sling.

4.1.3 Time on Task for Non-primary Vehicle Task

Table 16 summarizes the average time taken by each participant on the visor task as a function of sling use. The motion phase of the task took the longest on average. With sling use, the average time to perform the motion task was 3.55 seconds (SD=1.14) compared to 3.78 seconds

(SD=1.22) without sling use. The thinking aspect of the task was performed the fastest by participants on average. The average time on the response task was 0.681 seconds with the sling and 0.647 seconds without the sling. For motion, the longest task overall, the average times on task were 3.55 seconds and 3.78 seconds with and without the sling, respectively. Sling use was not a significant factor for thinking (p=0.0837), response (p=0.6804), or motion (p=0.5342) phases.

Table 16: Time to Complete Each Phase of Non-primary Task based on Sling Use

Average Time on Task (s)			
Sling?	Phase		
	Thinking (n=130)	Response (n=131)	Motion (n=124)
Yes	0.645	0.681	3.55
No	0.435	0.647	3.78
Standard Deviation (s)			
Yes	0.701	0.426	1.14
No	0.637	0.394	1.22

Overall, there is not a significant difference in the time spent on each subtask as part of the visor maneuver, disagreeing with the hypothesis**.** While slight differences do exist, they are negligible. This is likely due to the short time on task, likely related to the familiarity of the visor task both generally and throughout the drive. The second out of three visor tasks during each drive was selected, so participants were familiar with the task and had a previous encounter with it in their current state, which may have allowed them to troubleshoot any issues encountered. This leads to the idea that with practice and familiarity with the different behaviors, participants may be able to find successful adaptive mechanisms.

4.1.4 Behaviors Associated with Completion of Non-primary Vehicle Task

As video data were coded, it was noted that many participants appeared to bring the hand associated with the operative shoulder to the wheel before completing the non-primary task.

Only 20 observations of the operative hand on the wheel before the visor task were made when the sling was worn, in contrast to 62 observations of the hand on the wheel before the task when the sling was not worn (Table 17), a significant difference (p=0.0011). Participants were 3.5 times more likely to not have the operative hand on the wheel prior to the task when they were wearing a sling.

Table 17: Hand Associated with Corrective Operation on Wheel Prior to Non-primary Task based on Sling Use

Sling	Operative Hand on Wheel		
	Yes	No	N/A
Yes	20	24	2
No	62	21	0

A handful of participants did not complete the visor task in a fluid motion while both with and without sling use (Table 18), but this was a non-significant effect (p=0.6771).

Table 18: Completion of Non-primary Task in a Fluid Motion based on Sling Use

Sling	Complete Task in a Fluid Motion		
	Yes	No	N/A
Yes	43	4	3
No	72	5	7

While in the sling, no participant used the operative hand to reach up and change the position of the visor when instructed (Table 19). In contrast, when the sling was not worn, 10 participants used the operative hand to complete the task, a significant difference (p=0.0021). Overall, participants were at least 6.5 times more likely to use the non-operative hand to interact with the visor when they were wearing the sling.

Table 19: Associated Operative Hand Used on Non-Primary Task Performance based on Sling Use

Sling	Use of Operative Hand on Non-Primary Task		
	Operative Hand	Non-Operative Hand	N/A
Yes	**0**	48	2
No	**10**	74	0

The behaviors observed during the non-primary task based on sling use provide insight into the impact of mobility restrictions on driver behavior. Specifically, when analyzing the hand position of the hand associated with the operative extremity, **most drivers did not have this hand on the wheel prior to the instruction to complete the non-primary vehicle task when mobility restrictions were present.** This met the original hypothesis and shows the adoption of compensatory behavior.

It was also anticipated that there would be an observable decrease in the number of drivers able to complete the non-primary task in a fluid motion with sling use, but **the number of drivers completing the non-primary task in a fluid motion did not significantly change as a function of sling use.** With periods of interruption in the visor likely due to a need to maintain stability on the wheel, the lack of difference implies the use of other successful compensation, such as bringing non-operative extremity to the wheel for stability.

Finally, **every driver used the non-operative extremity hand to interact with and complete the non-primary vehicle task during periods of sling use,** as expected**.** Therefore, it was common for the operative extremity to be brought to the wheel for stability with the non-operative hand completing the task. The use of the sling is a partial mechanism to limit the range of motion. In this study, participants adhered to the intended limitation by not using the operative extremity to reach up and out of their limited range, as is necessary for healing. This adaptive behavior demonstrates resourcefulness by participants in order to complete non-primary tasks that are not essential to vehicle operation but commonplace with driving. These tasks may present similar requirements to those such as changing music or opening a sunroof, for example.

4.1.5 Steering Techniques Associated with Sling Use

Participants were 2.7 times more likely to use one-handed steering when they were wearing a sling (Table 20), a significant effect ($p<0.0001$). Observations where a hand position was unknown were omitted from the analysis. One- and two- handed steering, however, were observed with and without use of the sling.

Table 20: Number of Hands Used during Selected Steering Maneuvers based on Sling Use

Sling	Number of Hands Used	
	1 Hand	2 Hands
Yes	84,077	44,456
No	99,920	143,342

In agreement with the original hypothesis, analysis indicates that **the frequency of one-handed steering was greater during periods of sling use.** With mobility restrictions imposed from the sling, it is logical that more individuals adapt to a one-handed approach to maneuvering the vehicle. Of perhaps greater interest is the degree to which this adaptation is successful, which was assessed as part of the trajectory analysis and is discussed later in this chapter.

The relatively low odds of one-handed steering associated with sling use suggested the need to observe the relative prevalence of one-handed steering across drives. Indeed, the number of hands on the wheel during the steering maneuvers varied substantially as a function of drive (Table 21). One-handed steering was present across each of the drives, including the fully healed state at post-operative week 12. However, one-handed steering was highest during the drive at post-operative week 2, where sling use was the highest.

Table 21: Percentage of Hands Used for Steering Across Drives for Pre-selected Maneuvers

	Drive				
Hands Used	Pre-op	Post-op Week 2	Post-op Week 4	Post-op Week 6	Post-op Week 12
No Hands	0%	0%	0%	0%	0%
One Hand	39.3%	53.6%	51.3%	41.1%	33.6%
Two Hands	51.0%	28.2%	32.6%	50.0%	60.0%
Unknown	9.8%	18.2%	16.2%	8.9%	6.4%

The prevalence of one-handed steering before and after surgery influenced the odds of one-handed steering directly associated with sling use. Additionally, the largest among of unknown hand position occurred during periods of sling-use, as the sling and stiffness of the operative arm frequently resulted in a blocked view of the steering wheel.

Further exploration of the hand position during the visor maneuver showed wider variation between the most frequent placement for left hand position on the wheel compared to right hand on the wheel throughout the drives, along with wider variation in hand placement during the pre-operative drive and post-operative week 12 (Figure 6). During post-operative week 2, the most common hand placement was between 6 and 7 o'clock for the left operative extremity and between 4 and 5 o'clock for the right. At post-operative week 12, however, the most common placements had shifted between 8 and 9 o'clock and 2 and 3 o'clock for left and right operative extremities, respectively.

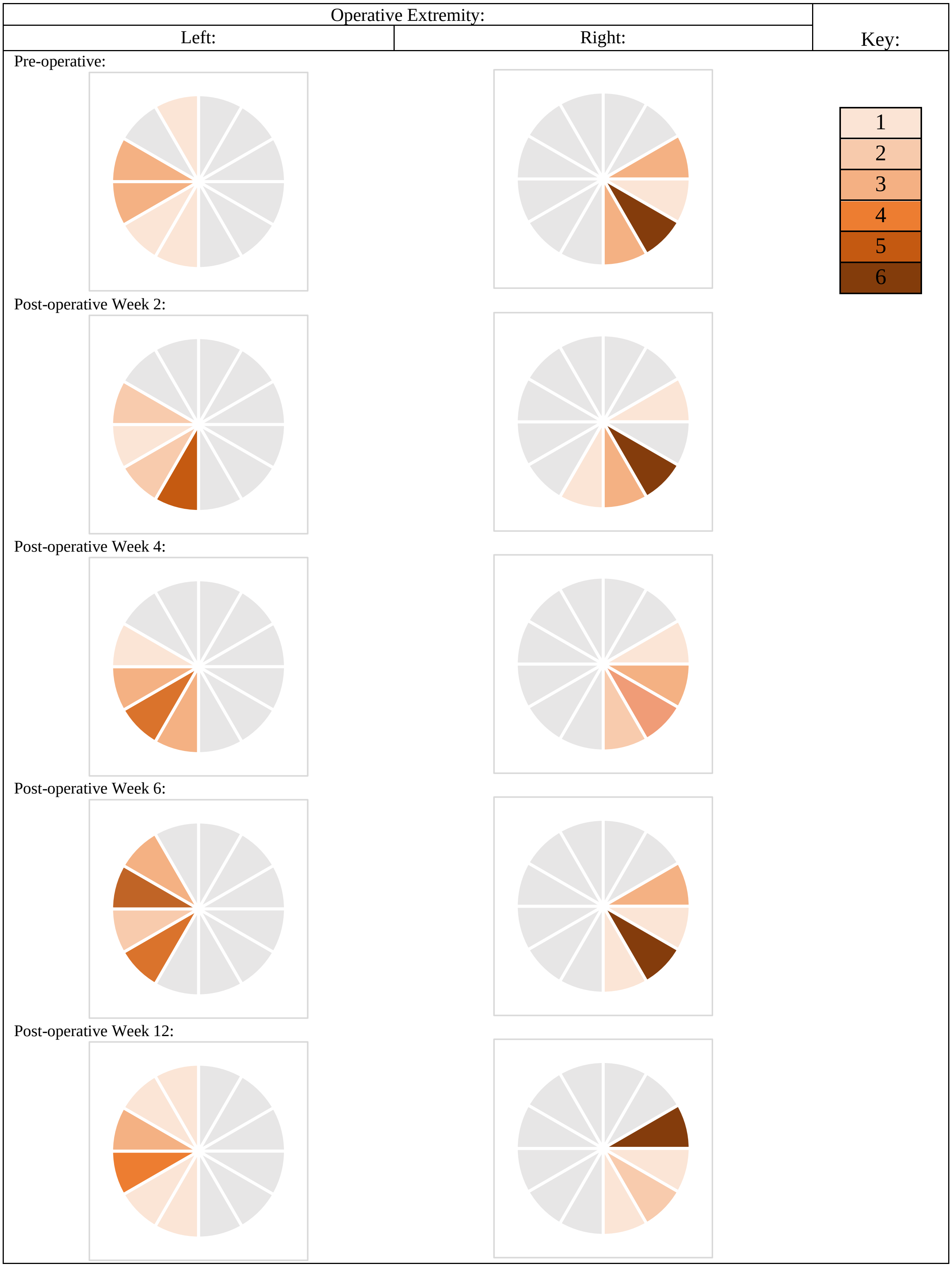

Figure 6: Frequency of Operative Hand Position on the Wheel at Different Operative Timepoints

4.2 Perceived Impairment

4.2.1 Kinematic Metrics Associated with Traversing Rough Terrain

Several trends and some significant effects were observed in the rough-terrain kinematic metrics as a function of operative time (Figure 7). No significant factors were found for the lateral and vertical acceleration range and or vertical jerk. For lateral jerk, however, operative timepoint was a significant factor, with a decrease observed across operative timepoints (p=0.0003). A Tukey's post-hoc test performed on the data revealed that the lateral jerk at post-operative week 6 and week 12 was significantly lower than that of the pre-operative drive.

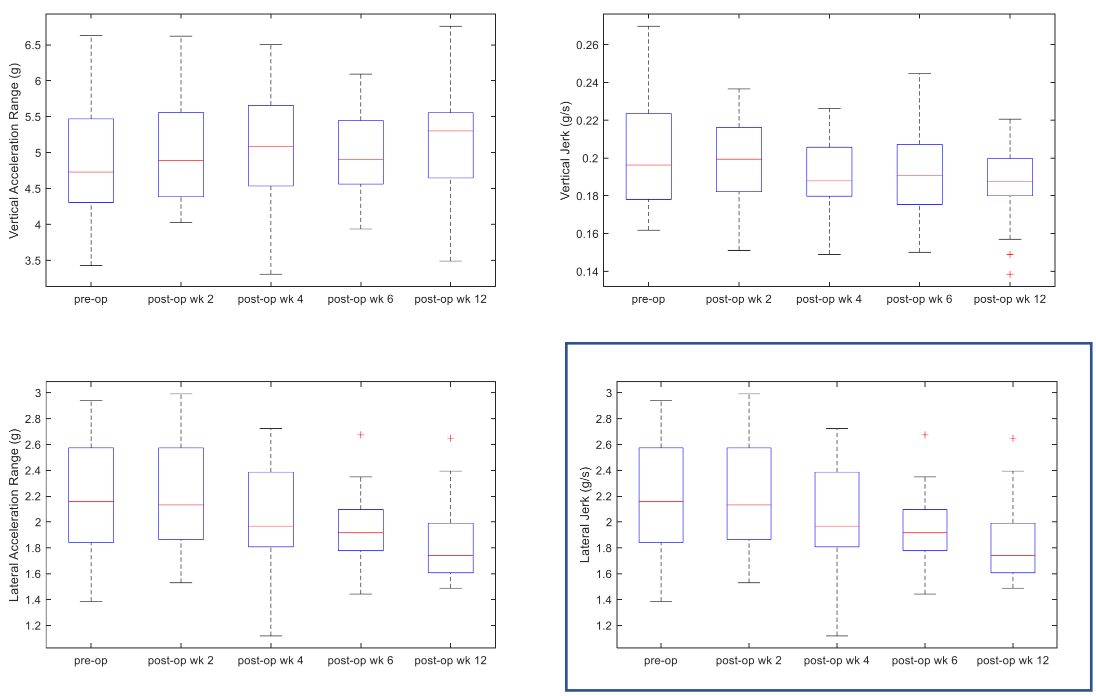

Figure 7: Kinematic Metrics Associated with Traversing Rough Terrains at Different Operative Timepoints

Overall, **the metric of lateral jerk was decreased during the post-operative week 6 and week 12 drives compared to the pre-operative drive, indicating a smoother passenger experience, while metrics associated with range of acceleration and vertical jerk were not significantly affected.** This somewhat disagrees with the initial expectation of adoption of smoother driving techniques during periods of perceived impairment. However, with increased two-handed steering during drives without sling wear, as was the case with all post-operative week 12 drives, the driver likely has more control over the vehicle and may create the smoother passenger experience that was observed.

4.2.2 Behaviors Associated with Traversing Rough Terrains

Only two instances of contact avoidance were observed during the pre-operative drive and post-operative week 12, and three instances of contact avoidance were observed during the drive at post-operative week 12 (Figure 8). No instances of contact avoidance were observed at post-operative week 4 and post-operative week 6. The operative timepoint was not a significant factor for the presence of contact avoidance (p=0.1009).

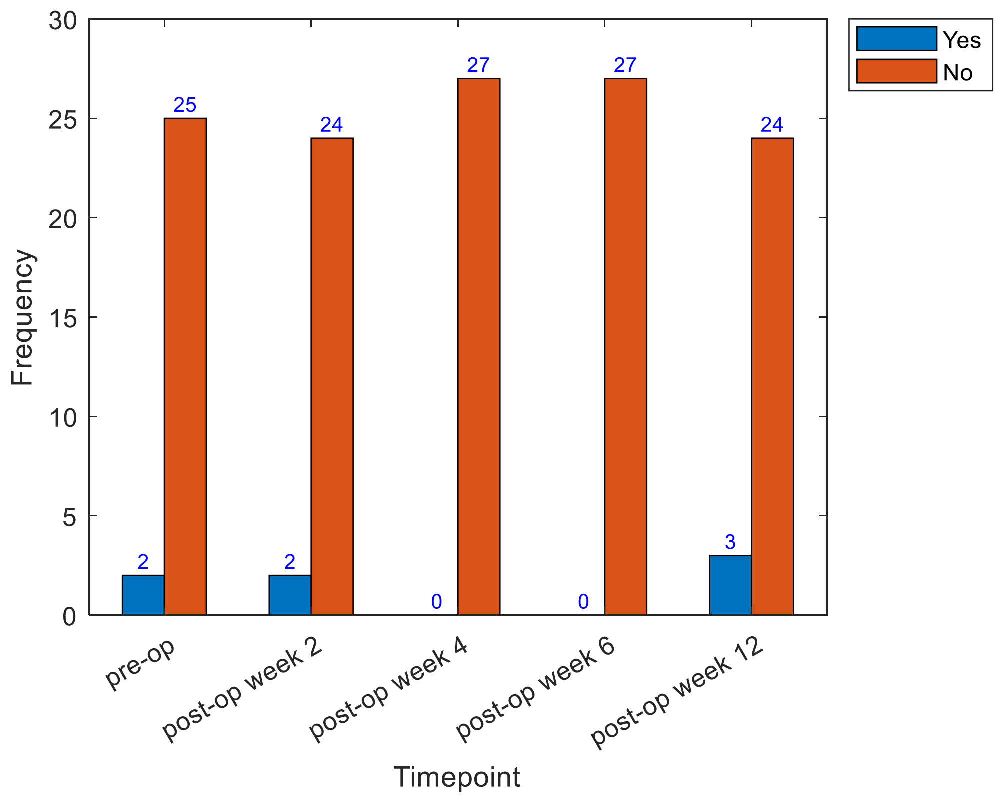

Figure 8: Contact Avoidance while Traversing Rough Terrain based on Operative Timepoint

Therefore, results of the analysis suggest that **contact avoidance with the interior vehicle cabin did not change significantly based on the operative timepoint.** Participants do not seem to perceive inferiority in this context and therefore are not substantially modifying their driving to ensure a smoother ride. Contact avoidance behavior was noted anecdotally by one of the in-vehicle experimenters and provides interesting insights on occasions in which it did occur, however, it was not a common adaptation.

4.2.3. Behaviors Associated with the Yield and Merge Maneuvers

The highest occurrence of looking over the shoulder during the maneuvers was observed at post-operative week 2, with 36 observed instances (Figure 9). The lowest occurrence of the behavior occurred at post-operative week 12 with 29 counts. This difference between all operative timepoints was not statistically significant (p=0.8126).

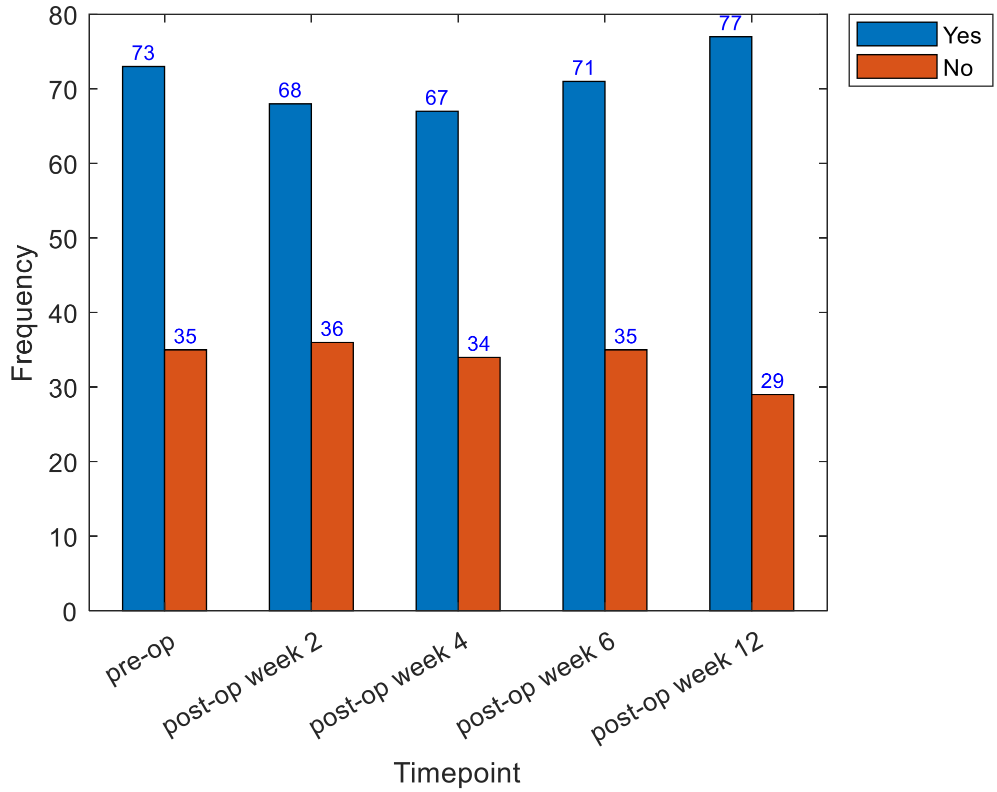

Figure 9: Looking Over the Shoulder during Yield and Merge Maneuvers based on Operative Timepoint

In a similar manner, the highest frequency of leaning forward occurred for participants during post-operative week 12 with 34 instances of the behavior recorded (Figure 10). The lowest frequency of leaning forward was found at the pre-operative drive with 24 counts recorded. Once again, these differences were not statistically significant (p=0.4747).

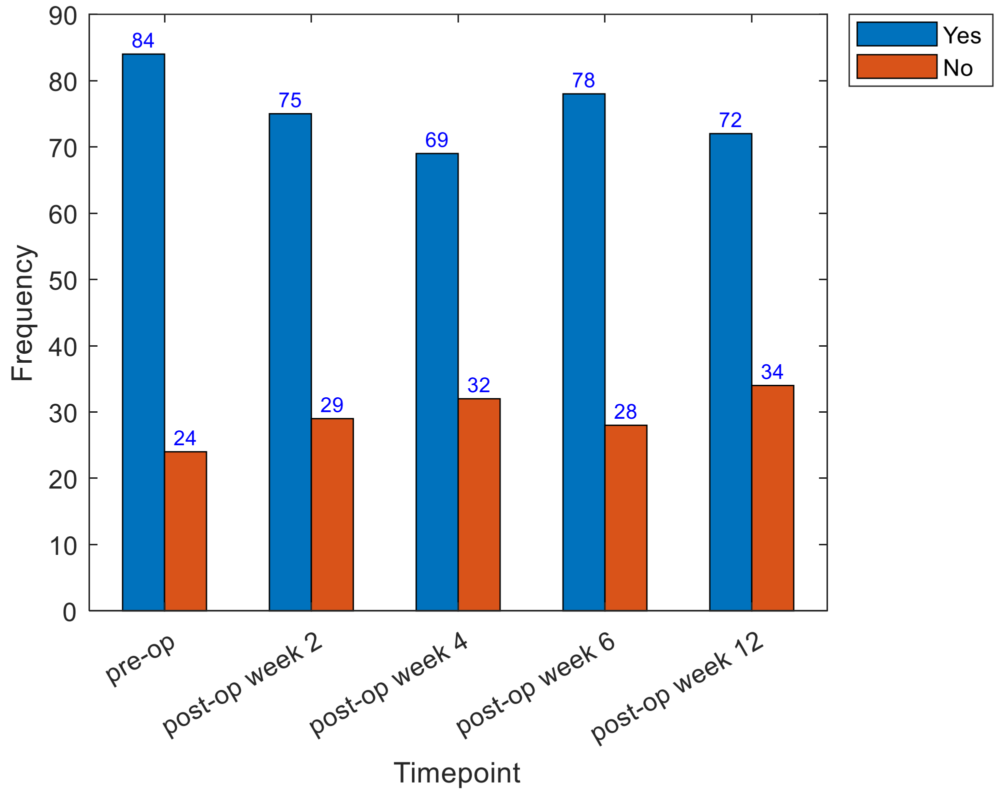

Figure 10: Leaning Forward during Yield and Merge Maneuvers based on Operative Timepoint

The highest amount of leaning forward occurred during the same operative timepoint as the lowest amount of looking of the shoulder: post-operative week 12. The inverse relationship between these behaviors is somewhat unsurprising, as one or the other can be used to check surroundings. Of interest, however, is that participants were able to look over their shoulder with similar frequencies to the other timepoints as early as pre-operative week 2. This demonstrates the ability to rotate the torso, and comfort with doing so, during instances of actual or perceived limited upper body mobility. Overall, **there was not a change associated with checking surroundings by looking over the shoulder as a function of operative timepoint. This**

observation was complemented by no significant change in leaning forward during periods of perceived impairment, in disagreement with the experimental hypotheses**.**

4.2.4 Turn Signal Use

While not specifically related to a specific research question, data exploration prompted the analysis of the frequency of the use of the turn signal on pre-selected maneuvers. The highest amount of turn signal use was seen at post-operative week 2, where every participant used the signal for each of the maneuvers (Figure 11). Conversely, the highest amount of non-compliance with the signal was observed during the pre-operative drive with 9 instances observed. Individual operative timepoints were a significant factor in use of the turn signal (p=0.0032).

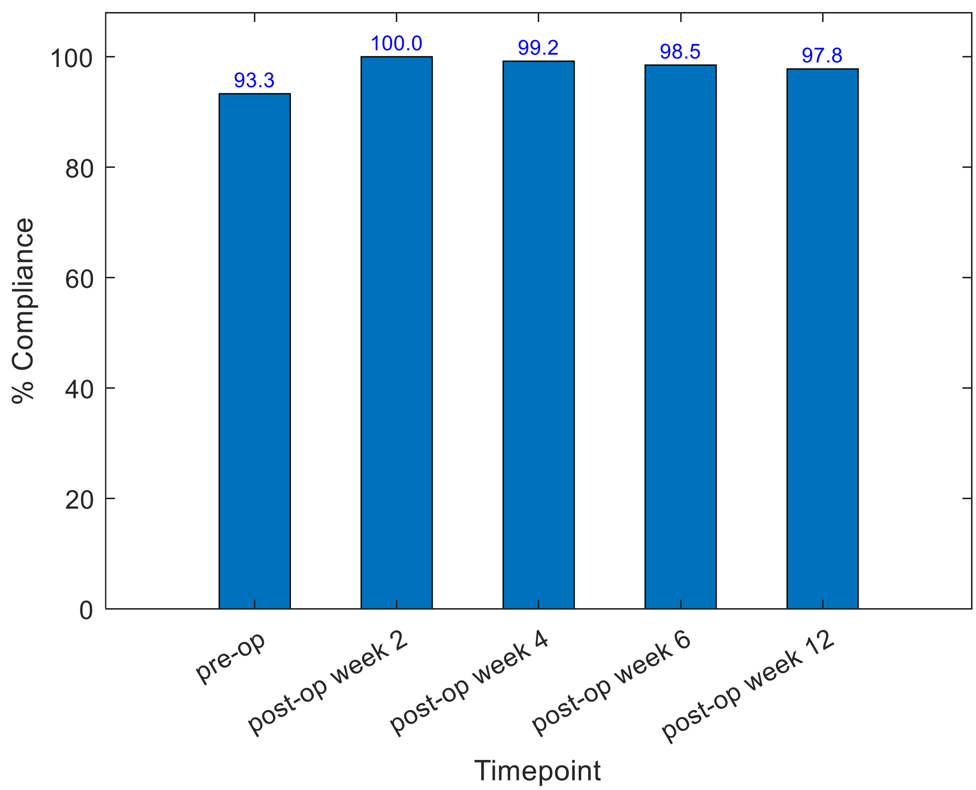

Figure 11: Percentage of Selected Maneuvers Which Turn Signal is Used Corresponding to Each Drive

The pre-operative drive having the highest amount of non-compliance in turn signal was somewhat counterintuitive. It would be reasonable to expect that drivers would present their best driving habits during the first drive and be on their “best behavior” with the in-vehicle experimenter. As comfort with the experimenter rose through successive drives, the drivers could be expected to be less cautious. This was not observed and suggests that the presence of the experimenter may not have been very influential on driving habits. The highest compliance immediately after the operation may also indicate drivers demonstrating better driving practices during the “riskiest” drive of the mix.

4.3 Quantification of Maneuver Success

The trajectory analysis was attempted for each of the turn types: standard left, standard right, straightaway, and non-standard left turn. With methodology followed and applied to each turn type, however, it was apparent that there existed major error in the GPS coordinates from the selected non-standard left turn. Ideal x and y points did not line up with the GPS curve, indicating the probability of an interruption of GPS signal within this maneuver (e.g., due to an urban GPS “canyon”). Therefore, the non-standard left turn was excluded from subsequent analysis.

4.3.1 Differences in Trajectory Error Across Sling Use

For each of the maneuvers selected for trajectory analysis, the final displacement error between the ideal trajectory and the bicycle model trajectory was recorded and divided based on drives with and without the sling (Figure 12). The average final displacement error when the sling was worn was 0.96 meters compared to an error of 0.98 meters when the sling was not worn. Overall, sling use was not found to be a significant factor in the value of final displacement error (p=0.4832).

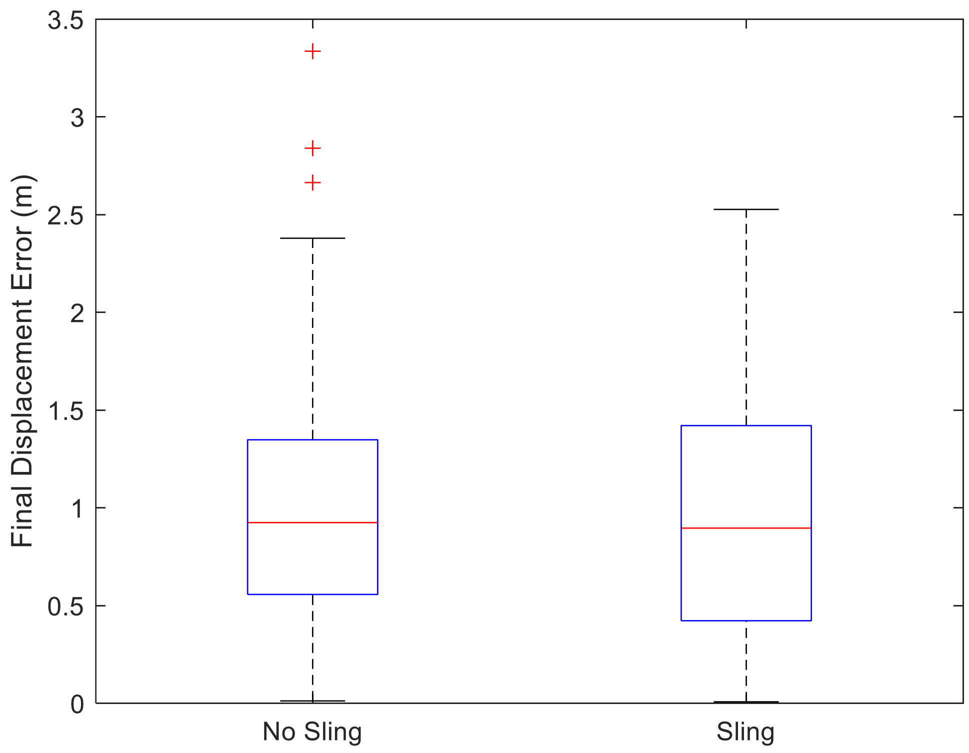

Figure 12: Final Displacement Error during Maneuvers Across Sling Use

In a similar manner, the average displacement error throughout the maneuvers at the pre-selected points was 1.36 meters with the sling and 1.18 meters without the sling (Figure 13). While slightly higher with the sling, sling use was not found to be a significant factor in determination of average displacement error (p=0.5634).

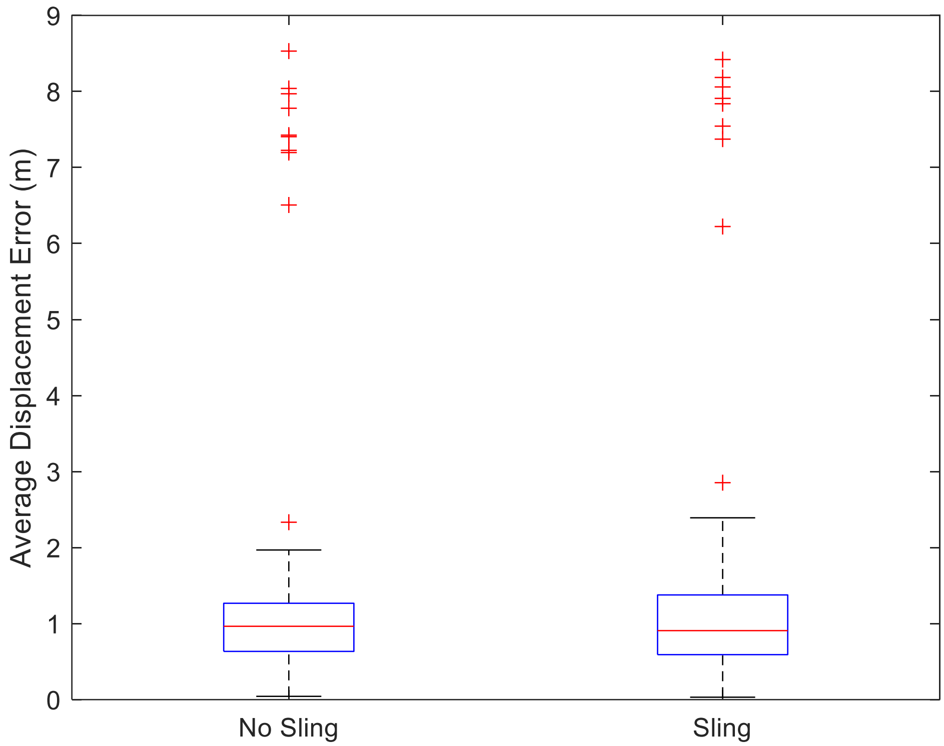

Figure 13: Average Displacement Error Across Sling Use

With sling-use producing non-significant differences in displacement error, it can be concluded that **mobility restrictions associated with sling-use do not impact completion of the ideal maneuver.** This finding supports the idea that drivers adopt successful compensatory behaviors for vehicle control, even prior to surgical intervention and the introduction of a sling. Drivers are able to complete turns with a similar level of accuracy regardless of their surgical status, which can be an important consideration for crash risk. If there were to exist a major difference in maneuver accuracy with the introduction of the sling, the trajectory differences could cause potential collisions with curbs, signs, and other vehicles. The lack of a detectable difference supports the argument of a quicker return to drive even with sling use.

4.3.2 Comparison Among Ipsilateral Turns

In completion of the standard left turn, the final displacement error for participants with a left operative extremity was 1.34 meters. Participants with a right operative extremity performing the same maneuver had a final displacement error of 1.13 meters (Figure 14). The increase in final displacement for the left operative patients was found to be significant during the left turn ($p=0.0138$).

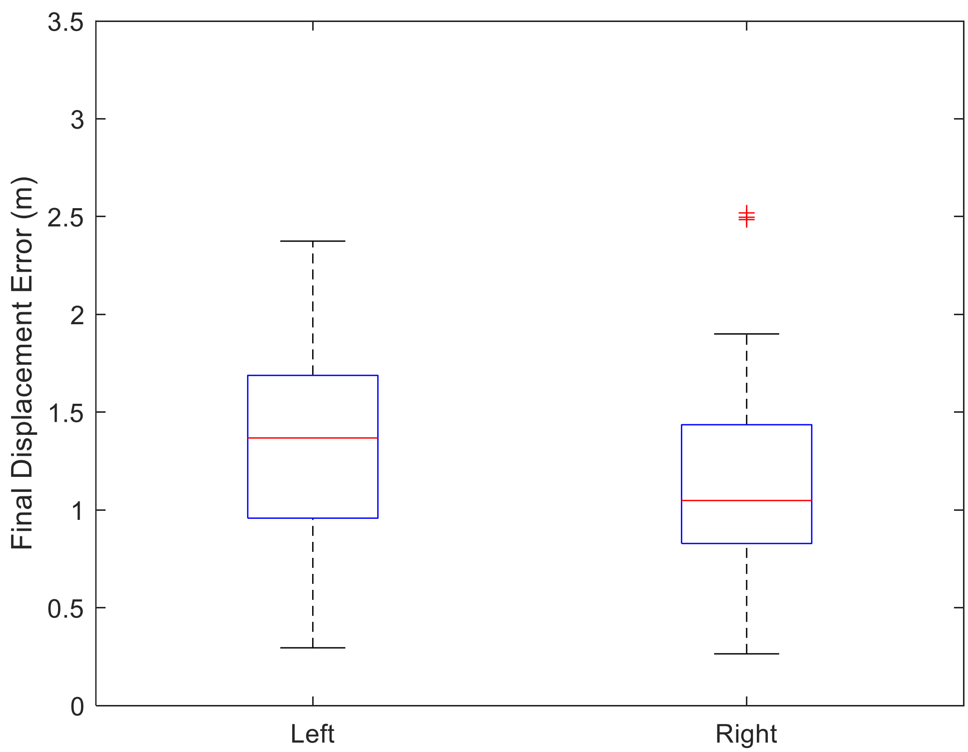

Figure 14: Final Displacement Error for Left Turn Across Operative Extremity

There was also a significant increase in average displacement error in the left turn maneuver for participants with a left operative extremity (Figure 15, $p=0.0264$). The left operative cohort had an average displacement error of 1.12 meters on the ipsilateral maneuver while the right cohort had an error of 1.04 meters on average.

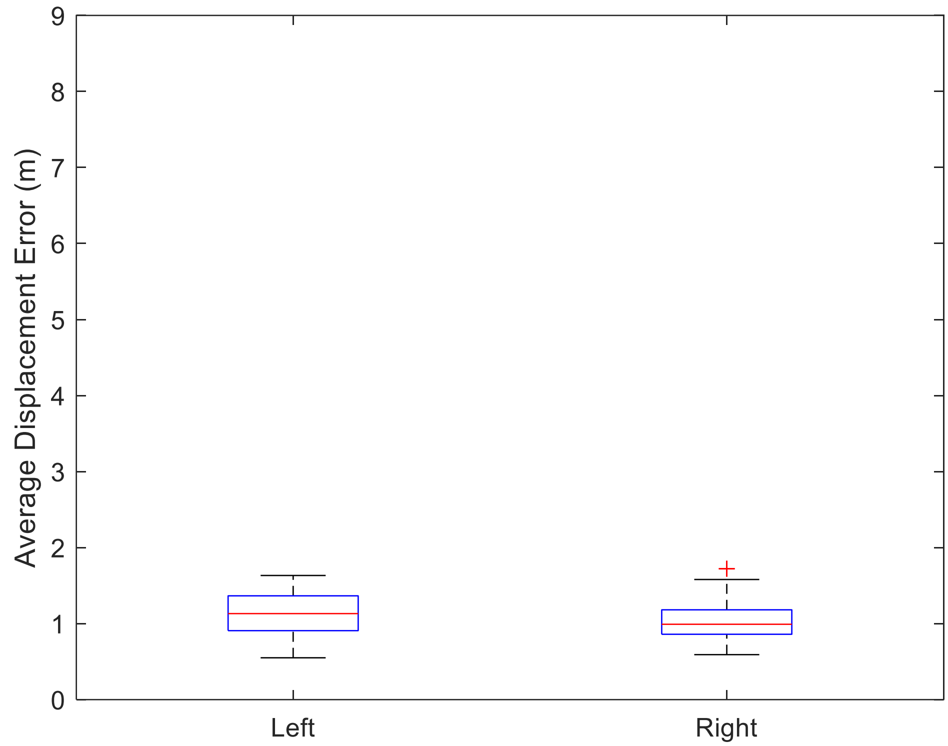

Figure 15:Average Displacement Error for Left Turn Across Operative Extremity

For the right turn, the final displacement error for those with a right operative extremity was 0.71 meters compared to 0.91 meters from the left cohort (Figure 16). In this maneuver, operative extremity was not found to be a significant factor in final displacement error (p=0.2279), albeit the magnitude of the difference in errors exceeded the magnitude observed for the left turn (0.3m vs. 0.2m between operative extremities for the right and left turns, respectively).

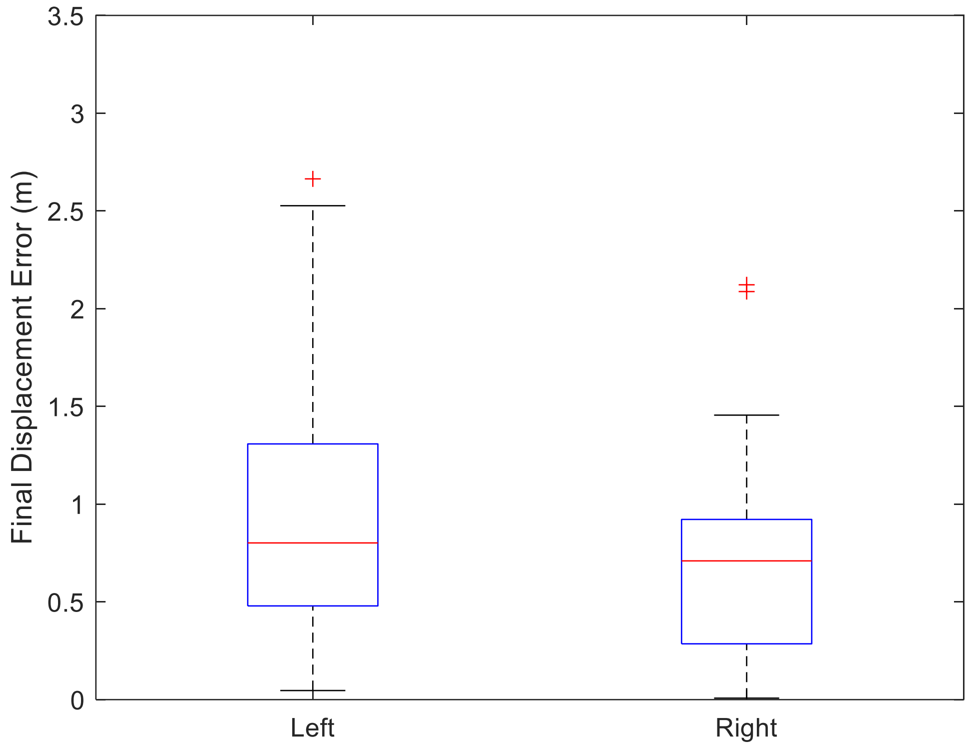

Figure 16: Final Displacement Error on Right Turn Across Operative Extremity

In comparing the average displacement error, the left cohort once again had a higher amount of error when considering the average displacement (Figure 17). The left operative group had an average displacement of 2.33 meters compared to the right operative group with 2.07 meters. However, operative extremity was not found to be a significant factor in the average displacement error during the right turn (p=0.7555).

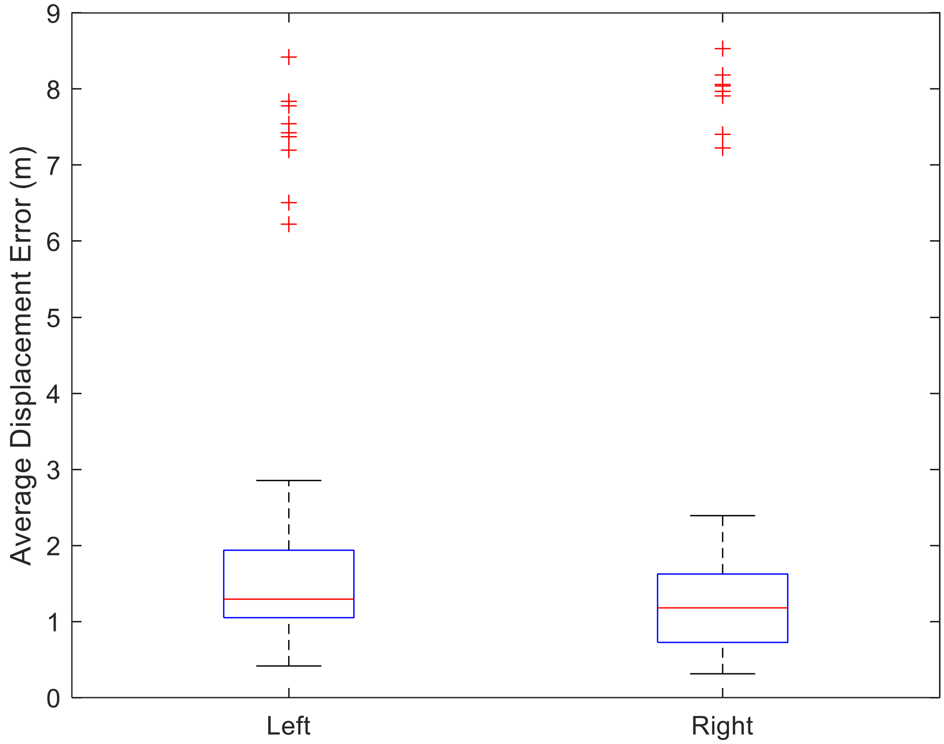

Figure 17: Average Displacement Error on Right Turn Across Operative Extremity

Overall, the findings from the displacement errors with the completion of turn ipsilateral to the operative extremity show mixed results. **For the left turns, there is a significant increase in the error with completion of maneuvers ipsilateral to the operative extremity. This was not observed for the maneuver ipsilateral to the right operative extremity, in spite of similar-magnitude differences across left and right turns.** A potential explanation for this difference is the reliance on left hand use in completing the maneuvers during vehicle operation. The loss of functionality of that hand, specifically on a maneuver with greater reliance on the left hand, is more apparent.

Differences between the left and right turns are likely due to the increased variance in the right turn trajectory. Participants had different approaches in these turns, likely producing more variability as well. The right turn occurred in the residential portion of the drive where street parking and pedestrians were more common, and lane lines were not explicitly marked. In contrast, lane boundaries were visible for the left turn, which occurred in a more urban part of the route.

Obstacles in the way of the ideal path for the left turn were less common, requiring less adaptation and deviation from this ideal maneuver. Nevertheless, the definition of the ideal path resulted in a certain level of sensitivity of the analysis to assumptions about vehicle position at maneuver entrance. Alternative approaches were considered in the definition of the ideal path, including using the pre-operative drive and using paths by “normal” drivers as “anchor” entry points. However, the pre-operative drive approach was not selected due to the pain and mobility restrictions from the injury itself before the corrective operation, which may impact the path that is used. In contrast, the “normal” driver approach would have required an assumption that these drivers are ideal. This approach would also be sensitive to temporary or transient obstacles on the roadway due to the nature of data acquisition on public roads.

Overall, the difference on the significant left-sided maneuver between the different operative extremities was 0.31 meters or approximately 1 foot. While the difference and significance are important to note, the average lane is approximately 10 feet wide (Ink, 2015) and the average car width is approximately 5.8 feet (Meyer, 2023), allowing for a fair amount of error in the maneuver. The observed difference between the two groups would not have placed the driver outside of the designated lane.

4.4 Usability of GPS Model

4.4.1 Comparison of GPS Accuracy to Actual Vehicle Path

Comparison of the final displacement between the GPS model and the actual vehicle path yielded from the bicycle model detected an average final difference of 2.97 meters (Figure 18). This difference in final displacement was significantly higher than the proposed 0.15-meter threshold difference (p<0.0001).

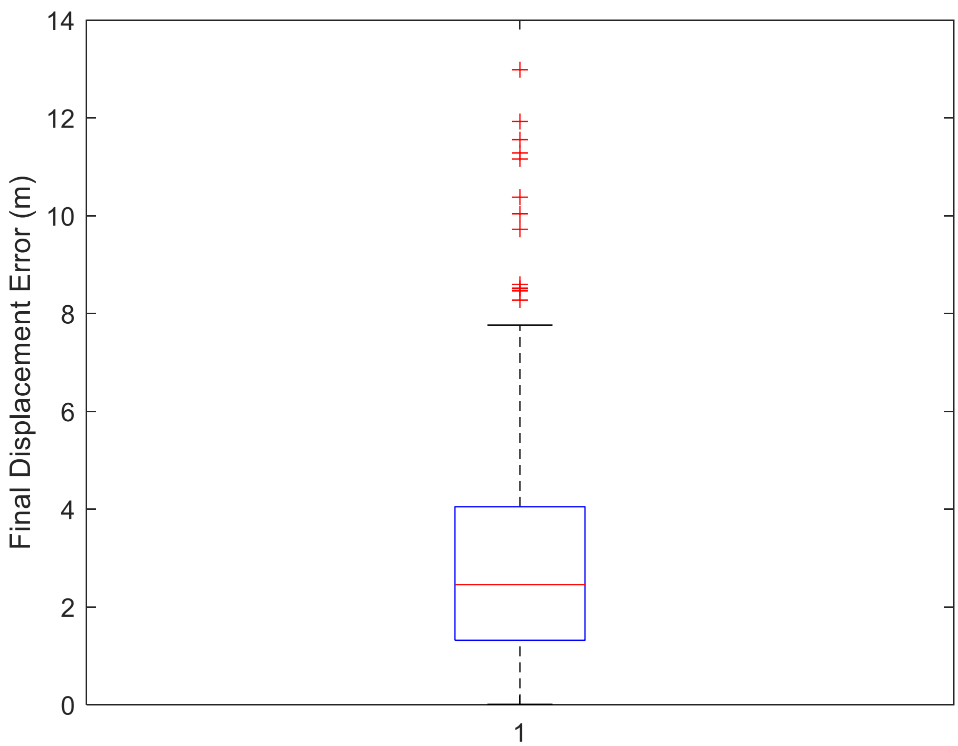

Figure 18: Final Displacement Error between GPS Model and Actual Path

In comparing the average displacement error between the models, an average final difference of 2.80 meters was observed. This difference was found to be significant in comparison to the proposed threshold error of 0.15 meters ($p<0.0001$).

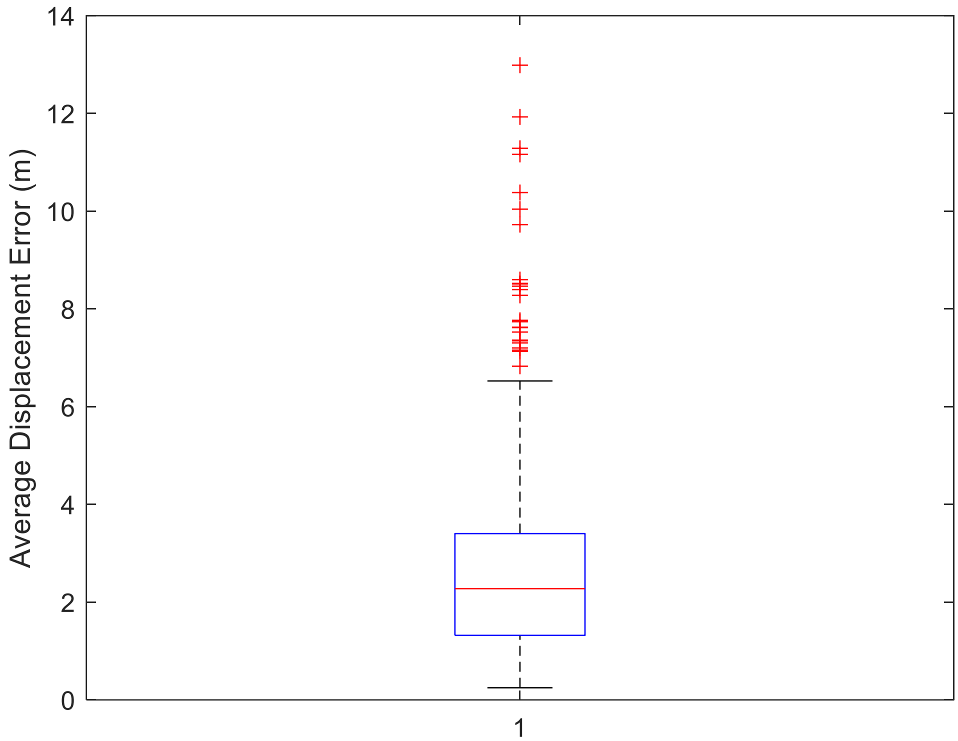

Figure 19: Average Displacement Error between GPS Model and Actual Path

The GPS model produced an error in terms of displacement well beyond the maximum proposed threshold of 0.15 meters. Informal visual inspection of GPS data traces throughout the analysis confirmed these results (e.g., Figures 20 and 21). Compared to the actual path, the GPS data appeared fairly inconsistent and was approximately off by almost a lane width. Furthermore, differences such as those depicted in Figure 21 verified that the GPS data did not suggest that the GPS was consistently offset from the ideal path, which would suggest possible and relatively straightforward corrections. Therefore, standard GPS appears to be insufficiently accurate in the determination of the actual position for these types of analyses. Differential GPS may provide better results, but implementation of these sensors may be more expensive than the kinematics-supported bicycle path approximations used in this investigation, which seemed to work reasonably well.

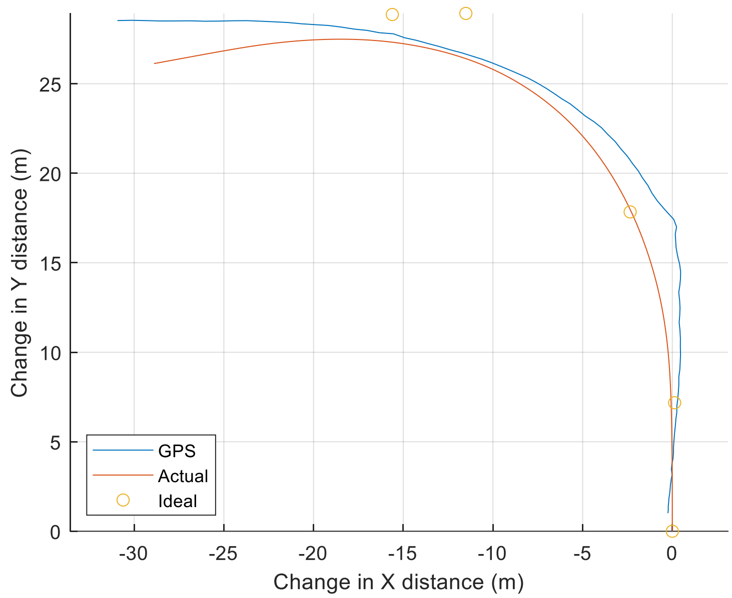

Figure 20: GPS Curve Aligning with Actual Vehicle Path

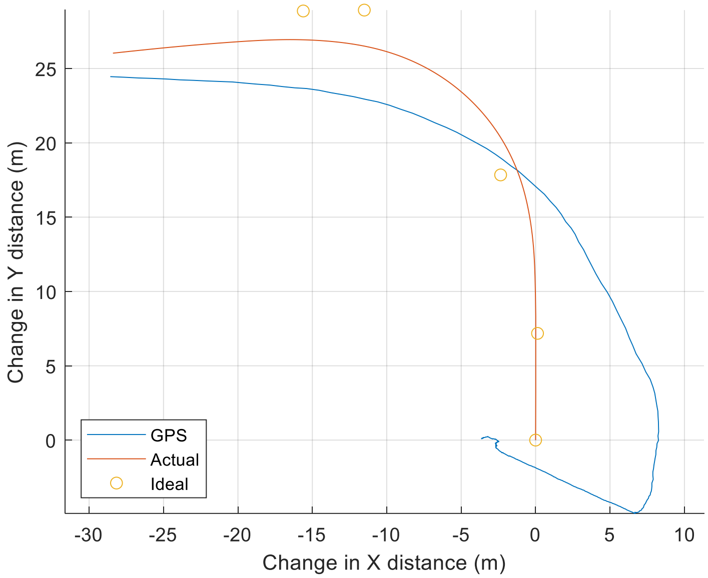

Figure 21: GPS Curve Not Aligning with Actual Vehicle Path

4.4.2 Comparison of Result Patterns Between the Models

Comparison of result patterns between the GPS and bicycle model paths against the ideal path showed a greater final displacement error from the GPS model (Figure 22, $p<0.0001$). The actual vehicle path had an average final displacement error of 1.25 meters compared to the ideal path. In contrast, the GPS model had an average final displacement error of 2.17 meters compared to the ideal path.

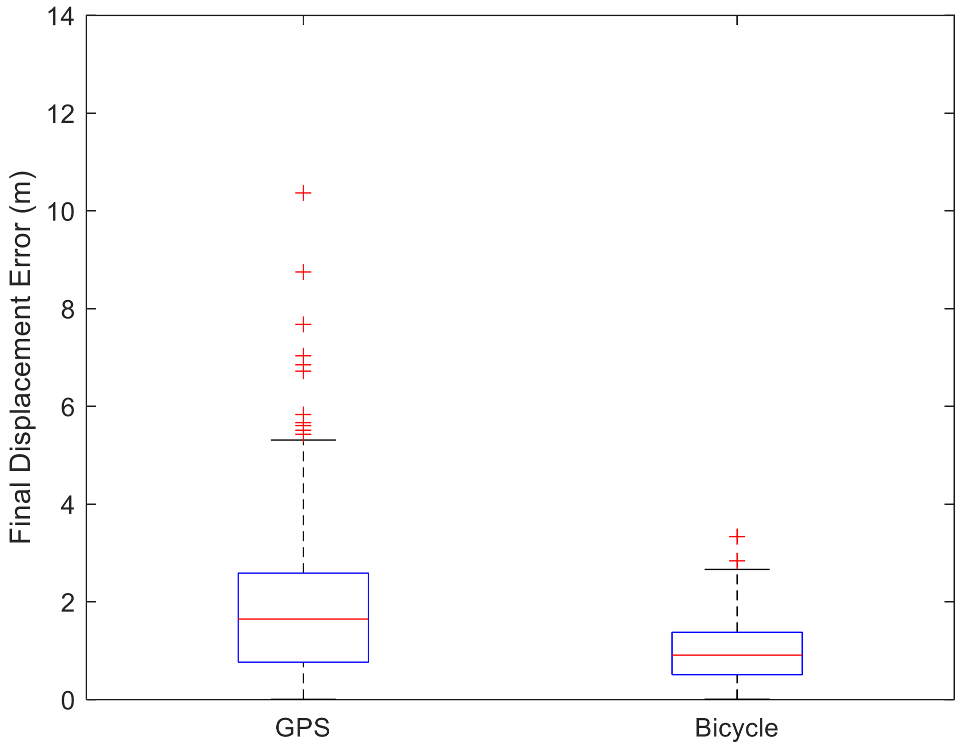

Figure 22: Final Displacement Error Across Model Type

In a similar manner, comparison of the average displacement error between selected points found an increase in average displacement error against the ideal path for the GPS model (1.94 meters) compared to the average displacement error of the actual path (0.974 meters, Figure 23, $p<0.0001$).

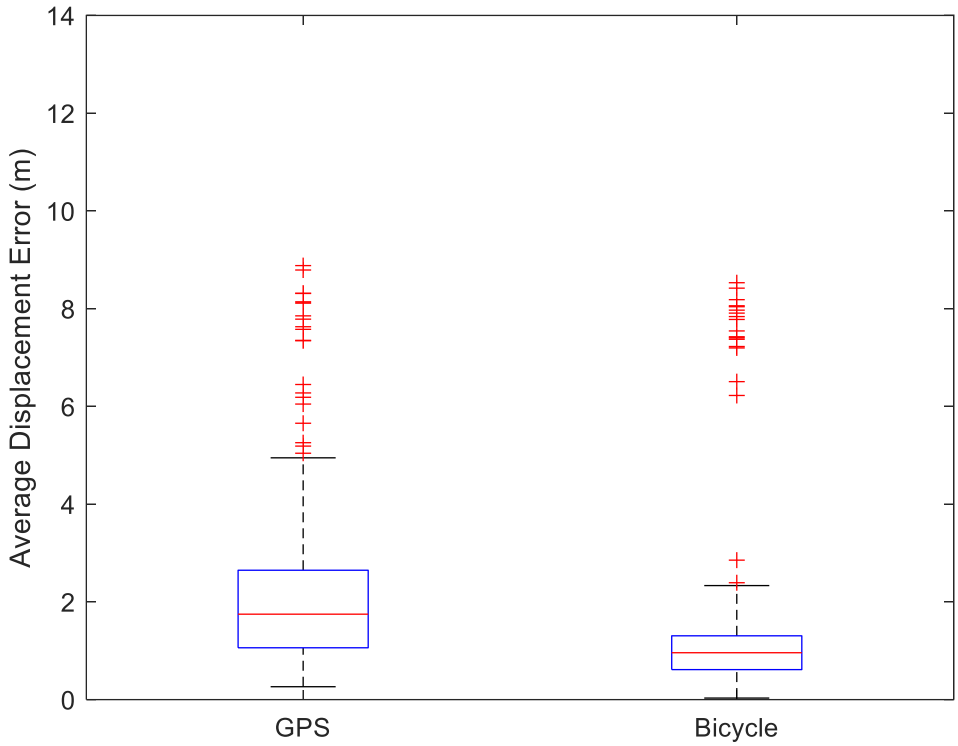

Figure 23:Average Displacement Error Across Model Type

In general, the GPS data provided fairly inaccurate results compared to the ideal path and the actual trajectory. **Therefore, the standard GPS did not produce an error profile similar enough to that of the actual vehicle path to be used as a replacement of vehicle kinematics in future similar efforts.**

4.5 Overall Implications in Return-to-Drive

Overall, behavioral and trajectory results indicate that patients can return-to-drive as early as two weeks post-operation. Participants were able to generally complete all instructed driving tasks during each operative timepoint. Additionally, the same number of interventions were required at post-operative week 2 as at post-operative week 12. The intervention at post-operative week 12 was due to the participant almost running a red light rather than a near crash with another vehicle.

Findings from the on-road assessment examined in this work found a non-significant change (difference of 0.18 meters) in average vehicle displacement error when sling use was present. Drivers, however, adopted some compensatory techniques to combat mobility restrictions including using the non-ipsilateral hand to control vehicle functions and one-handed steering. These observations partly confirm some of the findings in Hasan et al. (2015), who found an impact of sling use in driving.

Once again, as assessed in a simulator, Hasan et al. (2016) determined that driving performance was restored to the pre-operative level at post-operative week 6. Metrics assessed were the number of collisions, centerline crossings, and off-road excursions. Post-operative week 6 is typically when the sling is removed following rotator cuff repair. The non-significant minimal average and final difference in position between the drivers with and without a sling further validates that participants can steer within bounds and complete successful trajectories regardless of sling-use. Drivers were also still able to perform tasks critical to safe operation of the vehicle such as behaviors associated with evaluating surroundings and activating the turn signal. In fact, the highest compliance with turn signal use at post-operative week 2, the first assessment after surgical intervention, suggests that participants are perceiving a level of impairment and attempting to counteract that with positive driving practices.

Chapter 5-Conclusions

5.1 Summary of Findings

In revisiting the research questions and applying the results, a summary of the findings is described below.

1. **Do drivers compensate for mobility restrictions associated with upper extremity corrective operation?**
   a. Are there modifications in control of ipsilateral vehicle functions when mobility is restricted from sling use?
      i. Hypothesis 1a-i: There will be an increase in the number of drivers that use the non-ipsilateral hand to control the vehicle functions when the operative extremity is restricted from the sling.

         Agree- An increase in the number of drivers that use the non-ipsilateral hand to control the vehicle functions when the operative extremity is restricted from the sling.

      ii. Hypothesis 1a-ii: The number of drivers having trouble in control of ipsilateral vehicle functions will increase during states of sling use. For turn signal use, the greatest difficulty will be due to the hand not fully grasping, and therefore slipping, from the signal. In gear shifting, the greatest difficulty will be due to insufficient force to move the shifter to the correct gear for the maneuver.

         Somewhat agree- The number of drivers having trouble in control of the turn signal did not significantly increase during periods of sling use while the number of drivers having difficulty with the gear shifter

did increase with sling use. For the turn signal, the most frequent difficulty was due to slip, but not significant as a function of sling use. For gear shifting, the most frequent difficulty was due to insufficient force to move the shifter into the correct gear for the maneuver, which was significantly increased with sling use.

b. Are drivers able to perform non-primary vehicle tasks when mobility restrictions are present?

i. Hypothesis 1b-i: Drivers will need more time to prepare for non-primary tasks while in a sling, but the amount of time required to complete the dynamic task itself will decrease with sling use. Most drivers will not have the operative extremity on the wheel prior to instruction to complete non-primary tasks.

Somewhat agree- There is not a significant difference in the time spent on each subtask as part of the visor maneuver. Most drivers did not have this hand on the wheel prior to the instruction to complete the non-primary vehicle task when mobility restrictions were present.

ii. Hypothesis 1b-ii: The number of drivers able to complete non-primary tasks in a fluid motion will decrease with sling use.

Disagree- The number of drivers completing the non-primary task in a fluid motion did not significantly change as a function of sling use.

iii. Hypothesis 1b-iii: Most drivers will use the non-operative extremity hand to interact with and complete the non-primary vehicle task with the operative extremity on the wheel during periods of sling use.

Agree- Every driver used the non-operative extremity hand to interact with and complete the non-primary vehicle task during periods of sling use.

c. Do drivers adapt steering techniques used to perform driving maneuvers while using a sling?

    i. Hypothesis 1c: The amount of one-handed steering will be greater during periods of sling use.

    Agree- The frequency of one-handed steering was greater during periods of sling use.

2. Do drivers exhibit changes in behavior when impairment is perceived?

a. How do drivers modify vehicle behavior when traversing rough terrains, such as train tracks?

    i. Hypothesis 2a-i: Kinematic metrics such as jerk and range of acceleration will decrease during drives prior to 12 weeks post-operation.

    Somewhat agree- The metric of lateral jerk was decreased during the post-operative week 6 and 12 drives, indicating a smoother passenger experience, while metrics associated with range of acceleration and vertical jerk were not significantly affected.

    ii. Hypothesis 2a-ii: Drivers will modify body behavior to avoid contact with the vehicle interior cabin during the drives prior to 12 weeks post-operation.

    Disagree- Contact avoidance with the interior vehicle cabin did not change significantly based on the operative timepoint.

b. Do driver approaches to visually check surroundings change during periods of perceived impairment?

   i. Hypothesis 2b-i: Drivers will decrease looking over the shoulder during drives prior to 12 weeks post-operation.

      Disagree- There was not a change associated with checking surroundings by looking over the shoulder as a function of operative timepoint.

   ii. Hypothesis 2b-ii: Drivers will increase leaning forward during yield and merge maneuvers to increase the field of view and counteract decreased over-the-shoulder checks during drives prior to 12 weeks post-operation.

      Disagree- There was no significant change in leaning forward during periods of perceived impairment.

3. To what degree are drivers able to successfully complete maneuvers following rotator cuff corrective surgery?

a. Do mobility restrictions from sling use impact the completion of the ideal maneuver?

   i. Hypothesis 3a: Final displacement error and average displacement error will be greater for drives completed in a sling than those completed without a sling as measured through the comparison of actual vehicle path to the ideal path.

      Disagree- Mobility restrictions associated with sling use do not impact that completion of the ideal maneuver.

b. Are there impacts on the successful completion of maneuvers ipsilateral to the operative extremity?

    i. Hypothesis 3b: Final displacement error and average displacement error will be greater for maneuvers ipsilateral to the operative extremity as measured through the comparison of actual vehicle path to the ideal path. **Somewhat agree- For the left maneuvers, there is a significant increase in the error with completion of maneuvers ipsilateral to the operative extremity, which is not the case for the maneuver ipsilateral to the right operative extremity.**

4. **How accurate is path estimation derived from standard GPS coordinates compared to the actual path taken by the vehicle (as determined based on metrics from a data acquisition system and a vehicle parameter model)?**

    a. Is the GPS model able to describe the same vehicle behavior as the vehicle data-driven parameter model?

        i. Hypothesis 4a: The GPS model will have a suitable displacement error (within 0.15 meters) from the actual vehicle path. **Disagree- The GPS model produced an error in terms of displacement that was not within the proposed threshold range of 0.15 meters.**

    b. Do both the GPS model and the vehicle data-driven parameter model lead to the same result patterns?

        ii. Hypothesis 4b: The GPS model will have a similar error profile compared to the ideal path than the error profile between the actual path and ideal path.

Disagree- The GPS did not produce an error profile similar enough to that of the actual vehicle path to be used for analysis purposes.

Overall, the findings from these research questions can be translated into a set of post-operative driving recommendations. Specifically, more reliance on the non-operative extremity appears to be acceptable and is therefore recommended. This allows the non-operative hand to be employed in tasks that may otherwise violate the mobility restrictions of the operative extremity that are required for full healing. Such tasks include turn signal, gear shifter, and visor operation. Automatic-transmission vehicles, however, should be used by RTCR patients in contrast to manual-transmission vehicles (which require more frequent shifting in high-speed conditions). In addition, focus on the dynamic driving task should be emphasized for these patients. One-handed steering is useful to these drivers and appears to have the same level of success as two-handed driving within the conditions tested, and therefore may be used accordingly. However, drivers should be encouraged to be mindful of the limitations that they have when wearing a sling, particularly as it pertains to their ability to respond to emergency driving maneuvers. Therefore, patients should be encouraged to frequently and thoroughly check their surroundings to minimize the chances of having to engage in such emergency maneuvers. In the normal driving tested in this experiment, however, no drivers experienced re-injury.

Additionally, in order to minimize the need for quick maneuvers, drivers should attempt to minimize their highway driving. Anecdotally, drivers appeared uncomfortable at times during the highway merge and lane change maneuvers, and a few were unable to complete the quick lane changes required. The results provide no solid evidence to restrict highway driving, but alternative routes should be considered when feasible. In addition, when possible, drivers should back into parking spots. This allows drivers to avoid having to look over-the-shoulder while shifting gears, a somewhat difficult task after RTCR. Drivers should also self-assess their ability to don a seat belt. If unable to don a seatbelt independently, drivers should create a plan to have assistance with this task in preparation for their drive.

In general, however, if drivers are able to drive independently prior to RTCR, this investigation, combined with the findings of Badger, et al. (2022), suggests that they are able to return-to-drive at two weeks post-operation.

5.2 Limitations

Using public roads as a testbed, this study qualifies important evaluation elements of return-to-drive following arthroscopic rotator cuff repair. The on-road nature of the study allowed for a multitude of unique events and interactions to occur. However, no major emergency events occurred within the study to require the participants to perform evasive maneuvers. Experimenter intervention was seldom needed, and that need only occurred due to failure to obey a traffic law and not seeing another vehicle during a turn in the fully healed state. Emergency events were not explicitly excluded, as the study route had a strong representation of different roadway types where potential emergency events could occur. However, with a study conducted on actual roads, a surprise event could not be included or controlled in a feasible manner.

The study did include rapid lane changing in the short highway section. This required participants to quickly respond to traffic patterns and perform a quick maneuver. Additionally, in Thompson Orfield et al. (2020), a study analyzing the impact of a numb bandaged hand on driving fitness, the surprise event (as a surrogate for emergency responsiveness) did not yield significant differences in driving performance. Findings from that study may parallel what would occur rotator cuff repair patients.

The investigation was subject to several limitations. First, the influence and presence of the in-vehicle experimenter on driver behavior is not entirely known. The presence of the experimenter was very necessary, as this was the first on-road study of this specific injury. While some observations would suggest that the experimenter presence may not have always elicited drivers "best" behaviors, participants often tried talking to the experimenters during drives and were very much aware of their presence. Participants may also be more compliant in following recommendations for sling-use when under observation, although some participants did violate these recommendations. The findings of this investigation should be taken in that context.

Second, the study vehicle was different from that which the participants usually drove and may have had some effect on the study observations. In an attempt to mitigate the initial unfamiliarity with the vehicle, however, the parking lot maneuvers were used for the participants to become accustomed to the study vehicle before engaging in the rest of the drive, from which the maneuvers of interest were taken.

Third, the rear controls, necessary to increase participant and experimenter safety, may have influenced to some extent the handling of the vehicle. For example, the steering wheel felt tighter than in most light vehicles, particularly on initial exposure, and the brake felt firmer. As for the effects of unfamiliarity with the study vehicle, the main mitigation for these effects was the initial participant familiarization with the vehicle during the parking lot maneuvers.

Fourth, no two drives were identical in terms of the surrounding traffic experienced by the participant. Restrictions on time of day were made in an attempt to ensure that participants did not experience extreme traffic conditions. However, variable traffic interactions did occur, and the semi-controlled aspect of a public road study must be considered in the interpretation of the results due to the noise that they may have added to many of the metrics used in this investigation.

Finally, in terms of trajectories, a few assumptions had to be made. As an approximation and for simplification in model execution, the initial heading of the vehicle was always aligned to match the roadway heading. There is potentially some error in this assumption, particularly in certain roadway geometries. Additionally, the bicycle model converts a vehicle with four wheels into a vehicle with two wheels, losing some fidelity in the process. In addition, the use of Google Earth for the ideal path mapping results in only an approximation of such a path, with less precision than measurements taken from the actual roadway. The Google Earth software itself has inherent errors and requires minimum distances between points before computing the required waypoints. The overall effect of these assumptions and software limitations cannot be computed but was expected to be relatively small compared to hypothesized differences.

5.3 Future Work

This work, in combination with the work of Badger et al. (2022) is pivotal in determining when it is safe for arthroscopic rotator cuff repair patients to return-to-drive. Previously published official guidelines do not include such recommendations, and previous research was mainly completed with surveys and in driving simulators—inherently limited approaches. The on-road study approach used here represents an essential next step in generating research-driven return to drive recommendations. Those recommendations are based on analysis of compensatory behaviors and in the evaluation of the effectiveness of such behavior in driver trajectories.

Further analysis of this existing dataset could investigate the presence of additional compensatory behaviors. Eyeglance data, for example, would provide additional insight on drivers' ability and practices in checking their surroundings. Of particular interest is the use of mirrors, which was excluded in this investigation. Additionally, expansion of the analysis could examine the parking tasks—both parallel and perpendicular. This would extend examination of steering technique success into situations where participants are maneuvering the vehicle in a designated, bound area. Likewise, future work could examine participant approaches to don their seatbelt. Throughout the experiment, experimenters noticed that some participants needed assistance to buckle up, but data was not collected to document this difficulty.

With minimal safety critical interventions attributed to the injury itself observed in this study, the next logical step in this line of research is on-road assessment of patients without the presence of an in-vehicle experimenter. The expansion towards a more naturalistic study would provide greater insight into full driver behavior, including other compensatory behaviors used and adaptation in routes taken. The current work can serve as a basis in the analysis of behaviors used in future work. Additional future studies may also consider the impact of automation features on the behavior of patients with this type of temporary impairment.

Further work may also compare the accuracy of trajectories generated from a higher resolution GPS. Utilizing different GPS systems may provide insight into where the line may be drawn with respect to roadway position accuracy. Trade-off in resources and accuracy must continue to be considered within these processes. Additionally, in terms of trajectories, more maneuvers could be explored in the future to determine how to best select and analyze these maneuvers to more accurately estimate deviations from the ideal path that are caused by temporary driver impairment.

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Appendix A: Behavioral Maneuver Identification

Identification of Maneuvers of Interest- Shoulder Study

The purpose of this document is to introduce maneuvers of interests in the shoulder study. While each participant may have different experiences, it is believed that these are some common maneuvers to analyze for participants with or receiving shoulder surgery. Differing experiences emphasize the importance of multiple views to analyze the surroundings and conditions of the drive. At this stage of analysis, sixteen maneuvers of interest have been identified. Four of these maneuvers occur within the facility and are based on parking. The remaining twelve maneuvers occur on public roads. Due to potential restrictions of body movement, blind turns and fast merges are the most notable maneuvers of interests.

The directions are based on the In-Vehicle Experimenter Protocol document for this study. The comments are based on personal experiences on the course and aim to identify why each maneuver is of interest. All the landmarks for the maneuvers have been identified from the front car view unless otherwise specified. When looking at actual participants, this same view will be used to identify the maneuver to determine the timestamps for looking at different views. The timestamps for each of these maneuvers are based on the provided demonstrations videos. While timestamps will be different for participants based on factors such as driving speed and traffic, these timestamps allow the researcher to go back to reference videos in case participant maneuvers or surroundings are unclear.

Parking Lot/Within Facility:

Maneuver #1:

Direction: Please back out of this parking place, and head to left/right

Comments: This basic driving maneuver requires participant body movement to observe surroundings. This maneuver is dependent on the direction headed and the spot of the vehicle.

Beginning of Maneuver/Timestamp: Initial vehicle motion/ 626228:12412

- Vehicle is placed in reverse (View: Over the Shoulder)

End of Maneuver/Timestamp: Car begins pulling forward (put into drive) (View: Over the Shoulder)/ 643884:12939

Maneuver #2:

Direction: Turn (left or right, opposite as before) and drive up the next aisle.

Comments: This is the second U-turn maneuver. In isolating the second U-turn, it allows the driver to gain familiarity once again with the vehicle before evaluating the execution of the maneuver. This is dependent on the initial direction headed. U-turns require a range of body movement and tight turning of the wheel.

Beginning of Maneuver/Timestamp: When the cylindrical base of the left streetlight meets the corner of the screen/ 677187:13933

End of Maneuver/Timestamp: Dependent on initial direction traveled/ 693903:14432

- If down middle aisle: When the cylindrical base of the left streetlight meets the corner of the screen

- If down the leftmost aisle: When the cylindrical base of the right streetlight meets the corner of the screen (Different type of streetlight)

Maneuver #3:

Direction: Please parallel park the vehicle between the cones. When you are done parking, please put the vehicle into park and say "Done."
Comments: The parallel parking requires the participant to glance over the shoulder and may prove to be difficult. It may be interesting to see how the participant relies on the technology of the vehicle.
Beginning of Maneuver/Timestamp: Large Green Box on Right/ 877436:19910

- Vehicle is placed in reverse (View: Over the Shoulder)

End of Maneuver/Timestamp: Vehicle is put into park/ 928940:21434

- View: Front Face View

Maneuver #4:

Direction: Circle the entire roundabout before exiting the parking lot (you will go around 1 ½ times)
Comments: The roundabout requires the driver to hold the wheel and turn it in a certain way.
Beginning of Maneuver/Timestamp: Right as arch disappears from top view/ N/A
End of Maneuver/Timestamp: When the left side of the hood first meets the curb as the vehicle pulls out of the roundabout/ 1065722:25530

Roads/Outside of Facility:

Maneuver #5:

Direction: At the T, make a left on Carolina Ave.
Comments: This turn is a little tight. The elevation change makes looking up the hill hard.
Beginning of Maneuver/Timestamp: White Sign on Post on Left /1376161:34796

- A brown fence/parking lot are both visible to the left before the maneuver
- White house is straight ahead as stop is made

End of Maneuver/Timestamp: First Set of Power Lines to the Right/ 1392211:35275

- A white garage door with panels of windows is also to the left

Maneuver #6:

Direction: At the end of 28th St (1/10th mile), turn left onto Crystal Spring Ave.
Comments: This turn is somewhat blind due to cars which makes it difficult.
Beginning of Maneuver/Timestamp: Stop Sign to the Right/ 1474324:37726

End of Maneuver/Timestamp: When the Front Eave of the Porch of the White House on the Right meets the Edge of the Screen/ 1486855:38100

Maneuver #7:

Direction: At the stop sign at the top of the hill, make a left on Yellow Mountain Road.
Comments: This turn is a little tight.
Beginning of Maneuver/Timestamp: Brick House to the Right/Flashing Light Hanging on Top/ 1597281:41396

- Brick house with black shutters to the right as well
- Stop sign is on the right

End of Maneuver/Timestamp: 25 mph Sign on Post to the Right/ 1608068:41718

- Large powerline also visible

Maneuver #8:

Direction: Stay on Elm Ave. for about one mile.
Comments: This is maneuver aimed to analyze driving straight. It acts as a baseline, especially pertaining to hand placement.
Beginning of Maneuver/Timestamp: Pass through the first traffic light (light above is no longer visible)/ 1871268:49574

- Brick house with white front porch visible

End of Maneuver/Timestamp: Able to see large billboard on right side/ 1879844:49830

Maneuver #9:

Direction: Yield to traffic and merge onto Brandon Ave.

Comments: This intersection and merge requires participants to look over their left shoulder and merge into traffic. The oncoming traffic is not visible until at the intersection. It is also a 2-lane merge, which means there are sometimes vehicles immediately to the left of the car, obscuring the view of the oncoming traffic.
Beginning of Maneuver/Timestamp: Railing on Right /2116714:56900
*Note: If long red light (>10 seconds), may begin maneuver when vehicle resumes motion

End of Maneuver/Timestamp: First Power Line on the Right / 2125522:57163

Maneuver #10:

Direction: After crossing Grandin Road, ask participant to use visor again.
Comments: This maneuver is used to identify participant reaction to the visor instruction. It is the second time out of the three times this maneuver is performed by participant on drive.
Beginning of Maneuver/Timestamp: Preparation for lifting (or lowering) visor (e.g. hand released off of the wheel or other hand brought onto wheel)/ N/A

- View: Over the Shoulder
- Will be variable based on participant

End of Maneuver/Timestamp: When hand returns to contact the wheel/ N/A

- View: Over the Shoulder
- Will be variable based on participant

Maneuver #11:

Direction: Stay on Bridge St. for a quarter mile, go over the train tracks, and around the bend to the right to get on Patterson Ave.
Comments: For participants with left shoulder injury, the train tracks may cause some pain if the shoulder is bumped against while going over them. This may lead to modifications within driving behavior as well.
Beginning of Maneuver/Timestamp: Sloping Concrete Slab Attached to Guardrail before Railroad Crossing Sign/Light/Bars to the Right and Straight Ahead/ 2894552:80117

- Occurs right after crossing bridge
- Easily identifiable as tracks are visible in front car view

End of Maneuver/Timestamp: Pass the Yellow Right Turn Sign/ 2899745:80272

Maneuver #12:

Direction: Stay on Bridge St. for a quarter mile, go over the train tracks, and around the bend to the right to get on Patterson Ave.

Comments: This steep, blind, sharp turn may be difficult for participants.

Beginning of Maneuver/Timestamp: Back of Opposing Traffic Signage is Visible / 2904703:80420

End of Maneuver/Timestamp: Vehicle is Parallel to Large, Yellow Two-Legged Sign on Left/ 2911807:80632

Maneuver #13:

Direction: Stay on Patterson Ave. for 1.5 miles until it turns into Campbell Ave. Be careful, the first intersection you pass through has a hidden yield sign.

Comments: The hidden yield sign may be difficult because it requires the driver to look up and back (range of motion may be difficult/uncomfortable in the sling).

Beginning of Maneuver/Timestamp: Back of Yield Sign on Opposite Side of the Street (yield sign for oncoming traffic)/ 2939412:81456

- Fork in the road visible ahead

End of Maneuver/Timestamp: Able to See Silver Guardrail on Right/ 2954822:81916

- May also consider passing brick building on left
- Relatively easy to identify end of maneuver based on car movement

Maneuver #14:

Direction: In a quarter mile, at the 3rd traffic light, turn right onto Franklin Rd. (hard right)
Comments: As the directions indicate, this turn is a hard right. When the light is green, I anticipate that this maneuver will not be of interest. However, this turn has the potential to be a right turn on red. In this second case, this maneuver may cause interest. It is a sharp turn which requires a good range of body motion.
Beginning of Maneuver/Timestamp: Two-legged, Short Sign on Right/ 3246533:90623

- Around where the multi-color grey "cool" building is no longer in view

End of Maneuver/Timestamp: Where Straight Part of Left Median Meets the Car/ 3257021:90936

Maneuver #15:

Direction: Yield to traffic and merge onto highway. Make your way into the center lane.

Comments: Fast merges may be difficult with limited range of motion. This maneuver will be of interest, especially for those with left shoulder surgery. This is because merging requires them to look over their left shoulder.
Beginning of Maneuver/Timestamp: Guardrail is visible towards Left (upper part of screen) / 3422592:95878

End of Maneuver/Timestamp: May be variable based on participant (Front Car View relied on heavily)

- Look for when vehicle is completely in new lane/ 3449665:96686

Maneuver #16:

Direction: After passing the Colonial Ave. Exit, merge into the far-right lane.
Comments: Fast merges may be difficult with limited range of motion. This is the only lane change to the right within the study. This maneuver will be of interest, especially for those with right shoulder surgery. This is because merging requires them to look over their right shoulder.
Beginning of Maneuver/Timestamp: Prepping for lane change (e.g. looking in side view mirror or over shoulder) 3455258:96853

- May begin this maneuver after previous is completed

End of Maneuver/Timestamp: May be variable based on participant (Front Car View relied on heavily)

- Look for when vehicle is completely in new lane/ 3461523:97040

Appendix B: Discussion and Selection of Trajectory Maneuvers

Maneuver Identification for Trajectory Analysis

What we want:

1. Standard left turn
    a. Stop sign/stop bar before to serve as a centering point
    b. Standard/narrow lane size to somewhat minimize deviations in the lane
2. Standard right turn
    a. Stop sign/stop bar before to serve as a centering point
    b. Standard/narrow lane size to somewhat minimize deviations in the lane
3. Separate left or right turn
    a. Maybe a narrower turn
    b. Stop sign before to serve as a centering point
4. Straightaway
    a. Determine actual lane deviations in steering

*More TBD based on what comes out of these 4 scenarios

Potentially applicable pre-existing maneuvers discussion:

- Maneuver #5: Left turn on to Carolina
    - Does not begin with stop sign/light
    - Very narrow roadway but participants may creep into wide intersection to start since turn is very blind
    - Not a "standard" turn in that it is sharp (Less than 90°)
- Maneuver #6: Left turn on to Crystal
    - Begins with a stop sign
    - About a typical lane width but participants may creep into wide intersection due to the street parking making the turn somewhat blind
    - Pretty "standard" turn (~90°)
    - Wide area to turn into with street parking which may have impact
- Maneuver #7: Left turn on to Yellow
    - Begins with a stop sign
    - Roadway is standard width and is a 4 way stop which may reduce the likelihood for participants to creep into intersection
    - Not a "standard" turn in that it is sharp (Less than 90°)
- Maneuver #8: Straightaway
    - Standard lane width
    - Pretty uninterrupted in that participants typically do not have to respond to the actions of other vehicles
    - Change in elevation during maneuver
- Maneuver #12: Right turn on to Patterson
    - Does not begin with a stop sign/light
    - Not a true turn in that it is more of following a bend in the road to the right
- Maneuver #14: Right turn on Franklin (2)
    - Begins with a stop light

    - Participants are instructed to turn into the closest lane but often do not- unsure if this is due to ability or missing the instruction
    - Slightly wider than a standard 90° turn but variability based on lane turned into

Takeaways:

- Scenario 1 (Standard left turn): Probably beneficial to look for a new maneuver for this analysis alone
- Scenario 2 (Standard right turn): Probably beneficial to look for a new maneuver for this analysis alone
- Scenario 3 (Separate right or left turn): Maneuver #7-Left turn on to Patterson appears to be applicable at this stage
- Scenario 4 (Straightaway): Maneuver #8-Straightaway appears to be applicable at this stage

Potential new maneuvers discussion:

- Right turn on to Franklin (1)
    - Starts with a traffic light
    - Turn into two lanes of traffic so participants may not follow directions and turn into far lane
    - Close to a standard 90° turn
- Left turn on to Avenham
    - Starts with a yield sign
    - Follows a bend that crosses opposing traffic so not a true left turn
- Right turn on to Somerset
    - Does not begin with a formal stop of any sort
    - Narrow street to turn into which requires slightly more precision
    - Close to a standard 90° turn
- Left turn on to Clydesdale
    - Does not begin with a formal stop of any sort
    - Narrow street to turn into
    - Appears to be a slightly wide turn
- Right turn on to Avenham
    - Begins with a stop sign
    - Cross traffic does not have a stop sign but elevation may prevent creeping up since it is less blind
    - Close to a standard 90° turn
- Right turn on to Audubon
    - Does not start with a formal stop
    - Close to a standard 90° turn and has a change in elevation which could be interesting
    - Narrower roadway to turn into
- Right turn on to 28th
    - Does not start with a formal stop
    - Close to a standard 90° turn and has a change in elevation which could be interesting

- Narrower roadway to turn into
- Right turn on to 26^{th}
  - Begins with a stop sign
  - Cross traffic does not stop but it is a visible turn which may prevent creep
  - Close to a standard 90° turn
- Left turn on to Jefferson
  - Begins with a stop sign
  - Cross traffic does not stop but it is a visible turn which may prevent creep
  - Close to a standard 90° turn but wide turn area which may have an impact (area for cars to park on side of the road but they appear to not park as close to the intersection as with the Crystal Left)
- Right turn on to 24^{th}
  - Does not begin with a formal stop
  - Close to a standard 90° turn
  - Slight incline and very visible turn
- Right turn on to Jefferson
  - Starts with a light
  - Cross traffic has a light
  - Close to a standard 90° turn
  - Detour for a lot of participants
- Left turn on to Elm
  - Starts with a light so the cross bar would be used
  - Cross traffic has a light
  - Pretty standard 90° turn
  - Narrow turn area based on lane lines and opposing traffic
- Left turn on to Carlton
  - Does not begin with a formal stop
  - Cross traffic is stopped, and turn is somewhat narrow up the incline
  - Turn that was easily missed/given late instruction for which may affect the path
  - Close to a standard 90° turn
- Left turn on to Grandin
  - Begins with a stop sign
  - Opposing traffic does not stop but it is not as blind due to starting elevation
  - Often busy- time is not a relevant variable for this analysis so may not be a good or bad thing
    - Participants may slightly creep into intersection due to time and need for a quick maneuver
  - Wide area to turn into although there are lane lines intended to turn into
- Right turn on to Memorial
  - Begins with traffic light
  - Opposing traffic has a light
  - The curb makes this turn a little more than a standard turn
  - Narrow turn area to go into based on opposing traffic location

- Left turn on to Roanoke
  - Does not have a formal stop but must yield to oncoming traffic which is often the case
  - Lane lines but a somewhat wide area depending on where traffic is
  - Close to a standard 90° turn
- Right turn on to Bridge
  - Starts with a stop sign
  - Opposing traffic does not stop
  - Slightly wider than a standard turn
- Right turn on to 3rd
  - Starts with a traffic light
  - Opposing traffic stopped by a light
  - Street parking has potential to influence this turn and the curb is very rounded affecting the angle of the turn

Current Maneuvers:

- Scenario 1 (Standard left turn): Left turn on to Elm appears to be most applicable at this stage after evaluation of trade-offs
- Scenario 2 (Standard right turn): Right turn on to 26th appears to be more applicable
  - Right turn on to Avenham as back up but the Right turn on to 26th appears to have a slightly narrower lane to turn into
- Scenario 3 (Separate right or left turn): Maneuver #7-Left turn on to Yellow appears to be applicable at this stage
- Scenario 4 (Straightaway): Maneuver #8-Straightaway appears to be applicable at this stage

Potential Future Maneuvers:

- Left turn on to Crystal
  - Could be interesting to see how participants handle a wide turn area that does not have to be as precise
- Right turn on to Patterson
  - Could be interesting to see how participants follow a bend

Appendix C: Trajectory Specific Maneuver Identification

Trajectory Specific Maneuver Identification

The purpose of this document is to create a standard protocol for isolating maneuvers of interest for analysis in participant trajectory. Some of the maneuvers have already been isolated (See Maneuver Identification Document) as they overlap with behavioral maneuvers of interest.

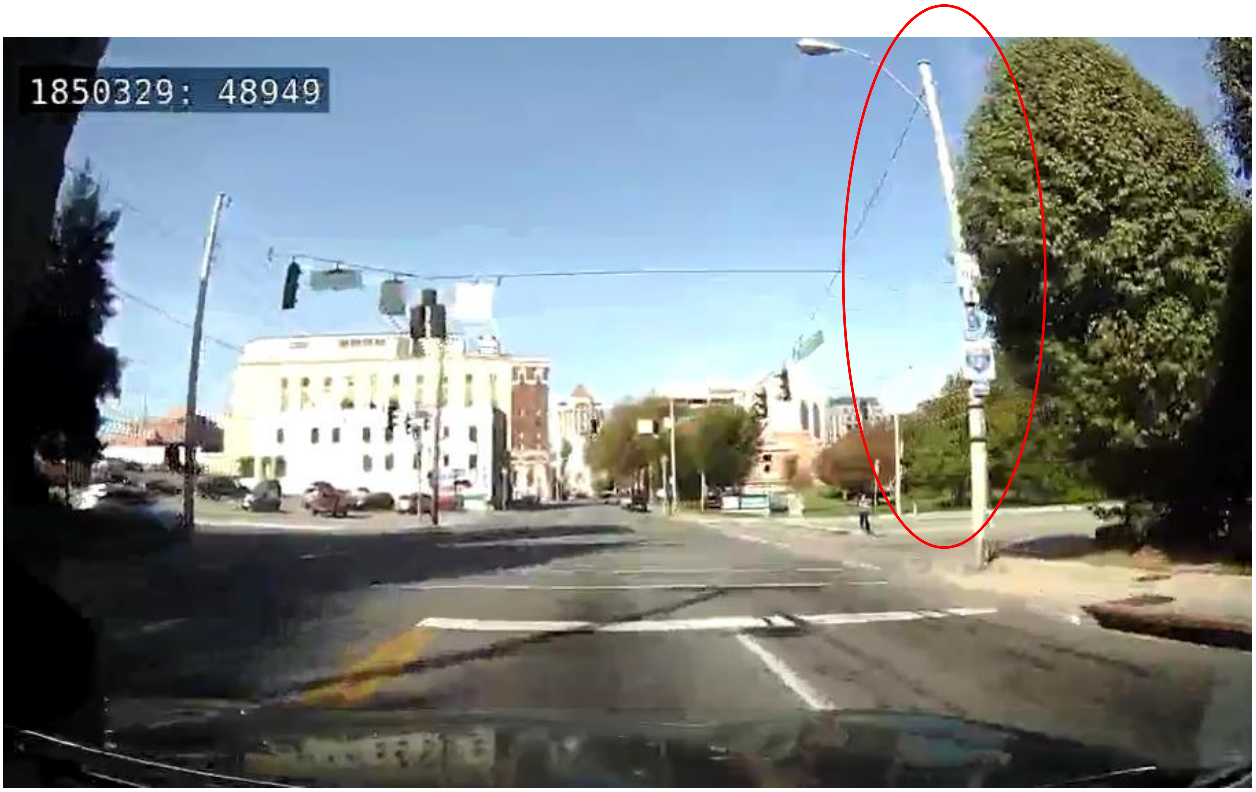
The directions are based on the In-Vehicle Experimenter Protocol document for this study. The comments are based on personal experiences on the course and aim to identify why each maneuver is of interest. All the landmarks for the maneuvers have been identified from the front car view unless otherwise specified. When looking at actual participants, this same view will be used to identify the maneuver to determine the timestamps for looking at different views. The timestamps for each of these maneuvers are based on the provided demonstrations videos. While timestamps will be different for participants based on factors such as driving speed and traffic, these timestamps allow the researcher to go back to reference videos in case participant maneuvers or surroundings are unclear.

Maneuver #1:

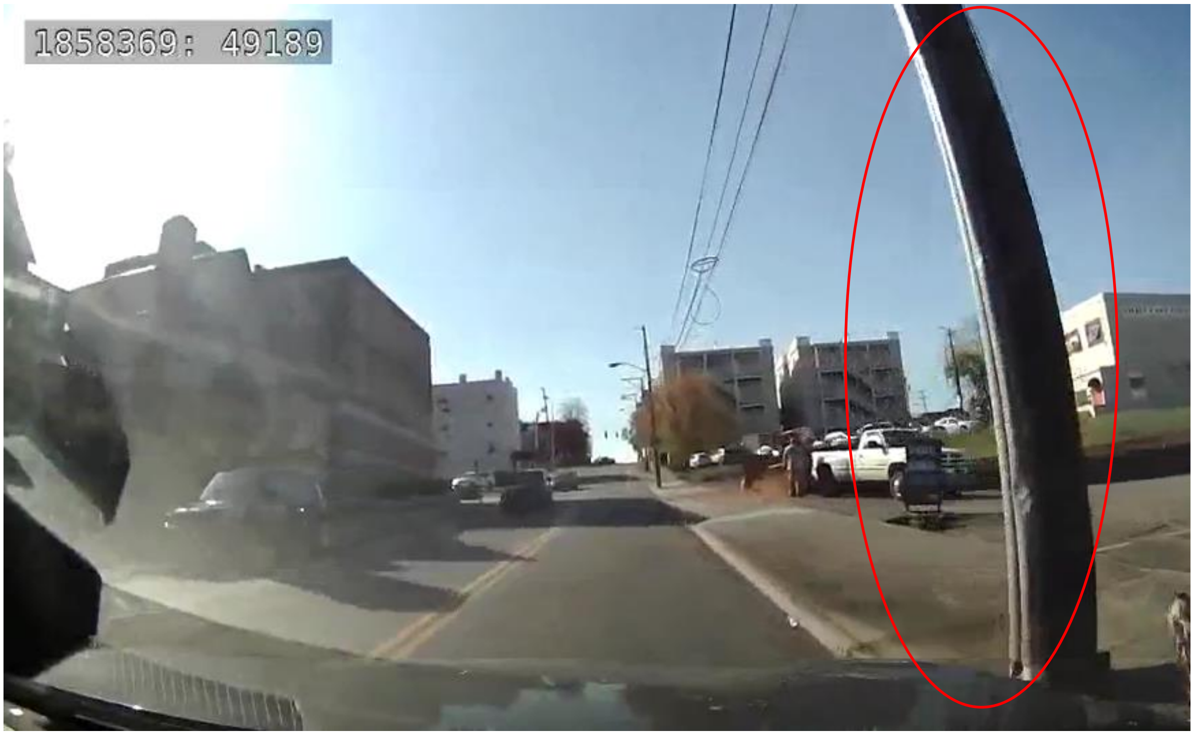
Direction: At the 2nd traffic light after Athen's Grill, make a left onto Elm Ave.

Comments: This is a standard left turn. This is a four-way intersection where all directions have traffic lights.

Beginning of Maneuver/Timestamp: Lamp Post on the right/ 1850329:48949



End of Maneuver/Timestamp: Lamp Post and powerlines on the right/ 1858369:49189



Maneuver #2:

Direction: At stop sign (< ¼ mile), turn right onto 26th Street.

Comments: This is a somewhat standard right turn controlled by a stop sign. The cross traffic does not have a stop, but the turn has better sightlines than many others in the study.

Beginning of Maneuver/Timestamp: Stop sign on the right/ 1511045:38822

End of Maneuver/Timestamp: Power lines on the left/ 1518582:39047


1518582: 39047

Appendix D: Behavioral Reduction Protocol

Experimental Driving Roanoke: Reduction Protocol

General:

- All data reduced for all given drives unless missing
- Operative hand determined from hand in sling during videos or given by Carilion personnel
- Operative hand in a sling is defined as the sling securing the elbow and the strap tightened

Hand Position Coding:

Purpose: The hand position coding reduction and analysis will be used to look at compensatory behavior and differences in steering techniques (i.e., one handed steering, wrist steering). Looking at a combination of parking lot maneuvers, left and right turns, and driving in straight road segments should provide insight into participant steering behavior and approaches. In comparing the pre-op to post-op drives, it may be determined if participants are exhibiting compensatory behaviors prior to surgery or when baseline steering abilities return.

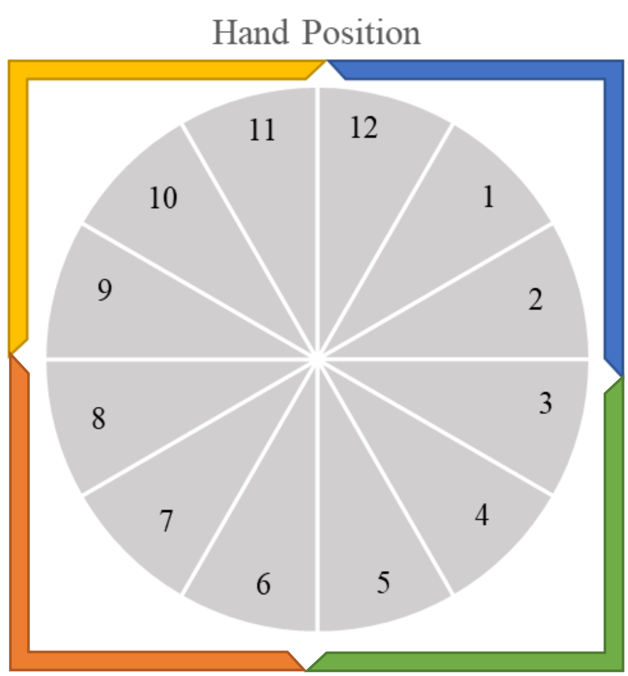
Maneuvers:

- M2: U-turn
- M4: Roundabout
- M5: Left turn on to Carolina
- M6: Left turn on to Crystal
- M7: Left turn on to Yellow
- M8: Straightaway
- M12: Right turn on to Patterson

- M14: Right turn on to Franklin

Methods:

- Observe hand position on the steering wheel on the over-the-shoulder and face camera views, primarily relying on the over-the shoulder view
  - Face view provides insight in instances such as the participant adjusting a face mask or raising hand before moving it to the next position
- Steering wheel is divided into segments like a clock with numbers corresponding to the following positions:



- As shown in the chart, the hand position numeric value is used to represent the section that overlaps with the time value
- The data may be collapsed into quadrants as follows:
  - Quadrant 1: 12-2 (Blue)

- Quadrant 2: 3-5 (Green)
- Quadrant 3: 6-8 (Orange)
- Quadrant 4: 9-11 (Yellow)

- The data also may be collapsed into upper and lower portions of the wheel:
  - Upper: Quadrants 1&4 (Blue & Yellow)
  - Lower: Quadrants 2&3 (Green & Orange)
- The "hand" in this coding encompasses the fingers, palm, and/or wrist of the participant
- In instances where areas of the hand may be in multiple positions, the coding is based on where the majority of the hand is located, generally, the position of the palm
- A loose grip on the wheel is still defined as the hand being on the wheel
- If the hand is not visible and some areas of the wheel are not fully visible, hand position is defined as unknown
- If the hand is not visible and the wheel is fully visible, hand position is defined as not on the wheel
- If the hand is seen off the wheel, hand position is defined as not on wheel

Visor Maneuver:

Purpose: The purpose of the visor reduction is to look at how the participant performs tasks that require a hand to be moved off the wheel and are not necessarily essential to the operation of the vehicle. The visor adjustment task typically requires two hands. This analysis will investigate how long it takes the participant to think through raising/lowering the visor, prepare for the maneuver, and raise/lower the visor. Additionally, observations about technique and hand position will be made.

Maneuvers:

- M10: Visor

Methods:

- The over-the-shoulder camera view will be used to record behaviors associated with the visor adjustment
- Timestamps synchronized with the video will be used to time different portions of the visor adjustment task, as follows:
  - Thinking through the action:
    - Start: Timing will begin after the first word of the direction statement is given
    - End: Timing will end when the first motor action from the participant begins
  - Response:
    - Start: Timing will begin when the first motor action from the participant begins

        - End: Timing will end when the participants hand first contacts the actual visor
    - Motion:
        - Start: Timing will begin when the participants hand first meets the actual visor
        - End: Timing will end when the participants hand returns to a resting position (wheel, lap, etc.)
        - Timing will not be considered if the visor maneuver is not performed correctly
            - Correct maneuver performance: raising and lowering the visor one time in either order
- The visor hand and wheel hands will be recorded
    - Visor hand: The hand(s) that contact the sun visor during the pre-defined maneuver
        - Options: Left, Right, N/A
        - If the operative hand is the same as the visor hand, the text of the cell in the Excel spreadsheet is changed to red for easier identification
    - Wheel hand: The hand (if any) that is in contact with the steering wheel during the motion portion of the visor maneuver
        - Options: Left, Right, N/A
        - If the operative hand is the same as the visor hand, the text of the cell in the Excel spreadsheet is changed to red for easier identification

- Wheel hand position recorded and defined by the hand coding rules presented in the previous section
- Observing whether the participant completes the visor task in a fluid motion
  - Fluid motion: Participant completes cycle of raising/lowering visor in one continuous motion.
    - Options: Yes or No
- Observing whether the operative hand is on the wheel prior to the visor manipulation (i.e., during the thinking stage)

Yield/Merge:

Purpose: Analyses of the yield and merge maneuvers will describe how participants sense, analyze, and act based on their surroundings while experiencing restricted upper body mobility. The yield and merge maneuvers will be analyzed to determine if participants look over their shoulder to see the oncoming traffic in blind spots and/or if they lean forward during the maneuver to get better visibility of surrounding traffic. This data will provide information about the level of mobility that participants have and the caution that the participants are taking.

Maneuvers:

- M9: Yield on to Brandon
- M13: Yield
- M15: Merge Left
    - First merge (merge from ramp to the right lane)
- M16: Merge Right
    - First merge (merge from the center lane to the right lane)

Methods:

- Coding based on the front and over-the-shoulder camera views
- Record whether each behavior was observed during the maneuver of interest:
    - Look over the shoulder to see oncoming traffic:
        - Options: Yes or No
            - Yes: The side of the participant's face meets or exceeds the plane extending from the shoulder consistent with the direction of the maneuver
            - No: The requirements for "yes" are not met

- Lean forward:
    - Options: Yes or No
        - Yes: The participant flexes their torso beyond the flexion induced by their sitting position prior to initiation of the maneuver
        - No: The requirements for “yes” are not met

Turn Signals:

Purpose: Observe and characterize the operation of a vehicle control that is essential for safe vehicle operation and can require a temporary release of the steering wheel by one of the driver's hands. For participants that have surgery on their left shoulder, activation of the turn signals may be difficult since the control is ipsilateral to the operative extremity. Additionally, both right- and left-side surgery participants may have trouble in balancing control of the steering wheel with manipulation of the turn signal, particularly when one of their arms is on a sling.

Maneuvers:

- M6: Left on to Crystal
- M7: Left on to Yellow
- M14: Left on to Franklin
- M15: Merge Left (Merge from ramp into right lane)
- M16: Merge Right (Merge from center lane into right lane)

Methods:

- Coding based on the over-the-shoulder camera view and the turn signal activation signal in the vehicle data
    - Face camera view also used in certain instances to assess difficulty experienced during the maneuver (see below)
    - Turn signal activation codes (in vehicle data):
        - 0=none
        - 1=left
        - 2=right

- Participants may activate the signal before the landmark defining the beginning of the maneuver- may have to go back in the video before the official maneuver begins to find the activation
    - May not go back further than previous direction/maneuver
- Hand:
    - Defined based on which hand contacts/activates the turn signal (if any) immediately before/during the maneuver
        - Options: Left, Right, Left/Right, or N/A
    - If there is an unsuccessful attempt at a turn signal activation, the hand is still recorded if the intent to activate is obvious
    - If there are multiple attempts to activate the turn signal with different hands, hands used in all instances are recorded
- Difficulty:
    - General:
        - Options: Some, No, or N/A
        - Some indicates one or more of the following conditions are met:
            - Insufficient force to activate the signal on an attempt
            - Hand slips from signal during operation
            - Losing control of the wheel during signal operation
            - Inability to operate the signal in the correct direction (does not apply if the participant did not comprehend directions)
            - Additional methods:

        - Face view may be used to gather expressions of surprise or frustration
        - Intended activation verified against the turn signal activation data stream
    - No: Indicates none of the above conditions were met but there was an attempt at signal activation
    - N/A: Indicates there was no attempt at signal activation
- Specific difficulty:
    - Slip: Failure to seamlessly operate signal on an attempt because of a misplacement or hand slipping from the signal
        - Options: Some, No, or N/A
        - Some: Failure condition is met during an attempt
        - No: Participant is able to activate the signal and has appropriate placement and control to activate the signal
        - N/A: There was no attempt to activate the signal
    - Force: Failure to operate signal on an attempt because enough force is not generated with the hand motion to fully activate the signal
        - Fully activate: The signal remains on after the participant attempts to activate it (i.e., no need to activate the signal twice)
        - Options: Some, No, or N/A
        - Some: Failure condition is met during an attempt
        - No: Participant is able to fully activate the signal by providing sufficient force

            - N/A: There was no attempt to activate the signal
        - Wheel Control: Losing control of the wheel during signal operation
            - Options: Some, No, or N/A
            - Some: Failure condition is met during an attempt
            - No: Participant maintains control of the wheel during and immediately following the signal activation
            - N/A: There was no attempt to activate the signal
        - Directionality: Temporary inability to operate the signal in the correct direction (does not apply if the participant did not comprehend the direction)
            - Options: Some, No, or N/A
            - Some: Failure condition is met during an attempt
            - No: The participant activates the signal in the correct direction or does so in the incorrect direction but does not apply an immediate fix (demonstrating a miscomprehension)
            - N/A: There was no attempt to activate the signal
- Difficulty does not include the participant holding or grasping the signal before activation or holding the signal for quick release, as these resonate more as preparatory/compensation techniques to successfully complete the task
- Holding the signal prior to activation:
    - Options: Yes, No, or N/A
        - Yes: The participant holds the signal X seconds prior to the motor movement activating the signal

        - No: The “yes” condition is not met
        - N/A: There was no attempt to activate the signal
- Holding signal for quick release:
    - Maneuvers: M15 (Merge Left) and M16 (Merge Right)
    - Options: Yes, No, or N/A
        - Yes: The participant’s hand remains on the signal in the activated position until released
        - No: The “yes” condition is not met
        - N/A: There was no attempt to activate the signal
- Techniques for hand usage on signal activation:
    - Options: N/A, Through, Around
        - N/A: The participant activates the signal with their left hand or does not attempt to activate the signal at all
        - Through: The participant activates the signal by accessing the signal from the opening in the steering wheel with right hand
        - Around: The participant activates the signal by reaching across the wheel without going through the opening in the steering wheel with right hand

Gear Shifting:

Purpose: The purpose of this reduction for analysis is similar to the turn signals. The analysis will focus on gear shifting, a required aspect of vehicle operation that is ipsilateral for participants that have surgery on their right shoulder. Comparisons will be made with turn signals in difficulty and hand used to operate the control. Additionally, both right- and left-side surgery participants may have trouble in balancing control of the steering wheel with manipulation of the gearshift, particularly when one of their arms is on a sling.

Maneuvers:

- M1: Reverse
- M3: Parallel Parking

Methods:

- Coding based on the over-the-shoulder camera view
- Hand:
    - Defined based on which hand contacts/activates the gear (if any) immediately before/during the maneuver
        - Options: Left, Right, or Left/Right
    - If there is an unsuccessful attempt at gear shifting, the hand is still recorded if the intent to activate is obvious
    - If there are multiple attempts at gear shifting with different hands, hands used in all instances are recorded
- Difficulty in the maneuver defined as:
    - General:
        - Options: Some or No

            - Some indicates one or more of the following conditions were met:
                - Hand slipping from the gear shift during attempt
                - Struggling with generation of force to move the gear shift on an attempt
                - Need to reposition hand during attempt
                - Vehicle is shifted into incorrect gear

- Specific difficulty:
    - Slip: Hand slipping from the gear shift during attempt
        - Options: Some or No
        - Some: Failure condition is met during an attempt
        - No: Hand does not slip from gear shift
    - Force: Struggling with generation of force to move the gear shift on an attempt
        - Options: Some or No
        - Some: Failure condition is met during an attempt
        - No: A sufficient amount of force is generated by the participant to move from one gear to another
    - Grasp: Need to reposition hand during attempt
        - Options: Some or No
        - Some: Failure condition is met during an attempt
        - No: Participant does not need to alter hand position to control the shifter
    - Directionality: Vehicle is shifted into incorrect gear
        - Options: Some or No
        - Some: Failure condition is met during an attempt

    - No: Vehicle is shifted into the correct gear for the maneuver

- Difficulty does not include the participant’s hand lingering on the gear shift as long as there is not an attempt to move the shifter into a different position unsuccessfully

Train-Track Crossing:

Purpose: During the study, participants had to cross train tracks, which induced erratic and sometimes high-magnitude oscillations in the vehicle roll. It will be observed whether, during these crossings, participants alter their body position to avoid contacting the vehicle door – especially in the case of a participant with a right operative extremity. Additionally, vertical acceleration will be analyzed to determine if the participant is attempting to reduce the impact or jerk felt from the train tracks.

Maneuvers:

- M11: Train Tracks

Methods:

- Coding based on the over-the-shoulder camera view and the vertical acceleration data
- Contact avoidance:
  - Contact avoidance: The participant alters body position as evidenced by lateral motion of shoulder in the direction opposite of the door
  - The window for contact observation is as follows:
    - Begin: The cross bar painted on the roadway
    - End: The cross bar painted on the roadway in the opposite lane
  - Options: Yes or No
    - Yes: Participant does demonstrate contact avoidance within given event as defined above
    - No: Participant does not demonstrate contact avoidance
- Reduced jerk:

- Max and min of vertical acceleration (Z-acceleration) and lateral acceleration (Y-acceleration) taken from DBVisualizer/MATLAB connection
  - Absolute maximum determined: Maximum magnitude between maximum and minimum acceleration
  - Range calculated: Range=Maximum Acceleration-Minimum Acceleration
  - Jerk calculated: Jerk= (Acceleration(i+1)-Acceleration(i))/(t(i+1)-t(i))
    - Maximum and minimum taken with absolute value (of maximum or minimum) reported