

Leveraging Digital Phenotyping to Monitor Glaucoma Severity Through Driving Habits

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Abstract— Glaucoma affects more than sixty million individuals globally and is the leading cause of blindness in elderly individuals over sixty years of age. Given that symptoms arise long after the initial damage has occurred, the current best course of action is to monitor the progression of the disease, ensuring that it does not reach a severe stage where it critically interferes with daily activity. Currently, there is no way to reverse the damage done by glaucoma. As such, this disease will pose an uncontrollable threat to patients' driving conditions, especially elderly patients. There are many driving monitoring software on the market, but none can help glaucoma patients diagnose their condition in real-time. In this study, we use digital phenotyping to help patients suffering from glaucoma. It will autonomously monitor the glaucoma patient's driving behavior, analyze the scores, and report them to the corresponding physician promptly to help the physician observe the patient's condition and conduct timely intervention.

Keywords— *Glaucoma, Digital Phenotyping, Driving Behavior, Smartphone Application, Visual Field Loss*

I. INTRODUCTION

Glaucoma is an ocular disease caused by increased intraocular pressure, leading to damage of the optic nerve, visual field defects, and—in advanced cases—blindness. It is one of the primary causes of blindness in elderly individuals aged sixty or over and the second cause of blindness across aggregated age groups. Presently, there is no cure for glaucoma. Any damage that has occurred to the optic nerve cannot be reversed. With populations growing and aging, the number of glaucoma patients is projected to increase [1]. Early detection is often the best preventative measure; however, many individuals relinquish the responsibility of the routine optometry check-ins necessary for quick

detection. By the time glaucoma is diagnosed in many individuals, the disease has often been present for a substantive time. Thus, a tool that consistently monitors an individual's ocular health and alerts the individual when suspected degraded eye health occurs is necessary [2].

For individuals with moderate glaucoma, the best course of action is to partake in regular exams and treatment to slow or prevent complete vision loss. However, the hassle of visiting the optometrist to gain a new data point regarding glaucoma progression can deter many patients from seeking regular therapy. Additionally, glaucoma can progress rapidly between optometry visits. Thus, it is necessary to develop a system that can consistently and unobtrusively monitor the progression of an individual's glaucoma, enabling the individual to solely seek necessary medical help when the disease progresses too quickly or to an advanced stage [3].

The aforementioned technological needs can be combined into a single application that monitors an individual's ocular health, alerting their physician if they are suspected of developing an ocular disease, if their ocular disease develops too quickly, or if their ocular disease develops to an advanced stage.

Figure 1 depicts an unobscured drive at an intersection against what a glaucoma patient driving might see. In this situation, a driver with visual field loss may miss the traffic light, the driver turning left ahead of them, and potentially passengers crossing the intersection.



Fig. 1. An unaffected visual field driving an intersection (right) versus a glaucoma-affected visual field driving an intersection (left).

Glaucoma & Driving Patterns

There exists a well-documented relationship between driving habits and glaucoma presence and severity. Glaucoma is negatively correlated with overall driver performance in both on-road (i.e., driving a predetermined course) and off-road (e.g., simulated driving or questionnaires) assessments. A 2016 study by Wood et al. found that individuals with glaucoma self-reported making two times as many critical errors than control groups. Notably, these errors commonly occurred at yield-give-way intersections and traffic lights, where access to one's entire field of view is vital [4]. In a similar study, Haymes et al. found that there were also three times as many patients with glaucoma that had critical at-fault interventions. Such situations were predominantly caused by the driver's failure to see and yield to a pedestrian. Within the population of individuals with glaucoma, Haymes et al. found that the patients' overall driving score decreased as their degree of visual field loss increased [5].

Notably, individuals with glaucoma tend to alter their driving practices or cease driving completely, actions that are highly dependent on the subject's degree of visual field loss. A 2013 study by van Landingham et al. found that 23% of subjects with glaucoma between the ages of sixty and eighty ceased driving completely compared to just 6.9% of the age-matched control group. Furthermore, the likelihood that a subject would cease driving doubled for every five-decibel decrement in the subject's better-eye visual field mean deviation (VFMD, i.e., the sensitivity of the subject's visual field compared to other individuals of a similar age) [6]. Driving conditions are also important for individuals with glaucoma. Individuals with glaucoma tend to prefer sunny and well-lit roads, as they find driving in foggy and night-time conditions exceedingly difficult.

Digital Phenotyping

Given that such well-documented relationships exist between an individual's driving patterns and their glaucoma severity, one could effectively monitor an individual's glaucoma through their driving habits. Such a technique is appealing, given its ease and unobtrusive nature. Driving events can be determined from the aggregate data of common sensors built into modern smartphones, such as accelerometers and gyroscopes. This makes developing a mobile application that tracks an individual's driving habits through their smartphone sensors a feasible and effective glaucoma monitoring application, a method commonly referred to as digital phenotyping. Digital phenotyping has been widely implemented to monitor behaviors and afflictions, such as spine disease and suicidal ideation, to an acclaimed degree of success [7][8]. The fusion of modern medicine and advanced technology often dramatically helps patients and physicians.

In this article, we will introduce the use of digital phenotyping to collect and analyze data collected from patients' digital devices to gain a more detailed understanding of the individuals themselves. Our method collects and analyzes the performance of drivers with glaucoma during driving, scores the driving safety factor, and uploads the scores to the physicians' terminals to help physicians analyze and judge the patient's condition and provide effective intervention.

The remainder of this paper is organized as follows: Section II provides an overview of the relevant existing driving behavior literature and digital phenotyping use cases. Section III describes the workflow of this project, the approach to developing the mobile application, and the structure of the system. Section IV covers the experimental results, limitations and their corresponding discussions, with Section V concluding this study.

II. RELATED WORK

It is reported that 97% of individuals in the United States own a cellphone, with 90% of owning smartphones [9]. Digital phenotyping, as previously discussed, holds significant promise in healthcare via mobile applications and increases accessibility. Within this domain, it is currently being utilized to assess various conditions, highlighting its potential for multifaceted clinical utility. Particularly, this technique has been used as a predictive tool in mental health, as evaluated in the 2002 review article by Chia and Zhang stating that 62% of the primary digital phenotyping published studies were aimed towards depression, bipolar disorder, and schizophrenia [10]. The emergence of this technique in 2016 needs further elucidation [11].

In the transportation sector, the proliferation of mobile applications has revolutionized the monitoring of driving behaviors and patterns. These applications serve diverse purposes, ranging from evaluating overall driving performance, identifying driving styles that are most fuel-efficient to facilitating the management of fleet businesses [12][13]. Despite their prevalence, none of these applications have been tailored to accommodate individuals with visual field loss.

In some studies, with primary focus on glaucoma and driving proficiency, subjects underwent a full ophthalmologic examination along with a driving questionnaire [14][15]. These examinations are informative and disclose a precise visual field chart which denotes the progression of glaucoma. However, these evaluations can be costly and may take an extended amount of time to complete. Alternatively, other studies imposed on patients with glaucoma to detect driving risk are conducted through driving simulations which is an efficient and convenient means to observe relationships which can be repeated and well-controlled [16][17]. This method, although ideal, may not result in the most organic behaviors since it is a synthetic environment as opposed to observation of natural driving.

Through sophisticated simulation environments, researchers have been able to empirically demonstrate and quantify the impact of glaucoma on various driving parameters.

III. METHODS

Before the application could be developed, a literature review was conducted to identify the driving patterns characteristic of individuals with glaucoma. The literature

review thus constituted the first phase of the project. Keywords “glaucoma,” “driving habits,” and “relationship” were inputted into academic article databases such as Google Scholar and PubMed. From the established reports of the driving behavior of glaucoma patients in both simulated and real driving studies, the maneuvers to pay consideration to varies but there is a generalized pattern in a delayed response to hazards, cornering, road signs [18]. The notable and detectable driving events will be expanded upon in the coming paragraphs.

A. Mobile Telematics

For this system's purposes, we require an undistruptive, customizable toolkit to collect mobile telematics that ensures that all driving data remains protected and assures no sale of data. The assessment of the toolkits evaluated is shown in Table 1.

TABLE I. COMPARISON OF DRIVE TELEMATICS SDKS

SDK	Open Source	Cross-Platform	Data Suitability	Use of Data
OSeven			✓	✓
MapBox	✓	✓		
Damoov	✓	✓	✓	✓
GeoTab	✓		✓	
DriveKit	✓		✓	✓
ZenDrive	✓	✓	✓	

We use Damoov’s Telematics SDK as it provides the infrastructure to detect and automatically track driving events and process driving data. The SDK also scores and analyzes trips based on braking, cornering, acceleration, and other driving maneuvers that align with the discussed driving behavior for patients with glaucoma. The application must adhere to HIPAA regulations for working with medical data. The Telematics SDK employs robust HTTPS encryption to ensure that all data collection and transmission is safe and visible only to authorized users. The SDK also shares our approach’s commitment to refrain from third-party data sharing and offers on-demand data destruction to enforce further sensitive information protection [19].

The basis for determining dangerous driving using the Telematics SDK and API is the summary safety score which is a grading from 0-100 aggregating a sum of points that factors in acceleration, braking, cornering, speeding and phone usage counts [20]. These driving metrics are weighted using the total length and mileage of each drive. All telematics are collected utilizing the gyroscope and accelerometer equipped on modern smartphones to gather the orientation and motion, then compared against speed limits, and expected driving conduct from the Google Maps API [21]. The formulas below enumerate how each score’s penalty is generated and calculated.

$$\text{Acceleration} = (0.0825 * S) + (1.0135 * D/1000 \text{ sec.}) + (0.1003 * F) \quad (1)$$

$$\text{Braking} = (0.1101 * S) + (0.7565 * D/1000) + (-0.0882 * F) \quad (2)$$

$$\text{Cornering} = (0.0825 * S) + (0.1422 * D/1000) \quad (3)$$

$$\text{Speeding} = 0.0434(0-24\text{mph}), 0.2372(25-34\text{mph}), 0.2929(35-65+\text{mph}) \quad (4)$$

$$\text{Phone Usage} = \text{speeding} * \text{event duration.} \quad (5)$$

S – recorded speed
 D – recorded drive duration
 F – recorded force

Input variables and coefficients are easily adaptable once the prominent parameters for glaucoma patients are ascertained for a customized scoring model. Damoov claims that their existing model analysis can establish a user’s driving style within a month and stabilizes results after three months [20]. The SDK also contextualizes smartphone driving events and provides flexibility with allocating penalties to each metric.

B. System Design

Our application uses Dart, a programming language that has cross-platform capability, to reduce time and make our application accessible on both Android and iOS devices. In conjunction with Flutter, Dart also provides many packages that can be used to parse data and expeditiously create layouts [22][23].

We require a secure backend service for user authentication, user role assignment, and enabling the SDK for smartphone drive monitoring. The Firebase platform was the most fitting for these requirements. Firebase configuration within a Flutter application has extensive documentation and a suite of services. We leveraged Firebase Authentication to facilitate the registration of both patient and physician accounts, credential retrieval, and the alteration of user passwords. Firebase’s Realtime Database enabled the storage of account credentials and tokens generated by the SDK we utilized for bearer authentication [24]. The bearer tokens are generated through an API call to Damoov’s data platform DataHub, simultaneously registering a patient in our system and their records.

Within each user’s stored credentials, we add data fields to discern between the user type (i.e., patient or physician), which is checked before a user signs in to guarantee no driving metrics are visible to unwarranted users. Within the patient registration form, there is a dropdown menu comprised of registered physicians they select from which Figure 2 illustrates the first level data flow diagram for patient user registration and authentication.

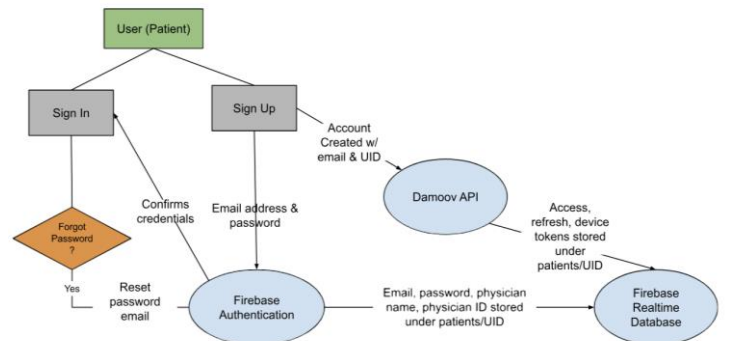


Fig. 2. Data flow diagram for user registration and authentication of patient type. An account is simultaneously created within Firebase and DataHub which will store driving data with the user’s email address.

For a physician, phone number, full name, and National Provider Identification (NPI) are also stored. We use the

National Plan and Provider Enumeration System's (NPPES) NPI API to verify the legitimacy of physician accounts. Every licensed healthcare provider is enrolled and given a unique NPI number which serves as an identification number. For the tracking to begin automatically, patients must grant permissions to the smartphone's location, motion, and sensors. Telematics SDK provides a pre-made permissions wizard, which we have customized for our application and is prompted to first-time users. We devised a method to use the device tokens to certify the patient and call the tracking API to detect the start and of drives automatically.

Approximately ten minutes after a drive is completed, the patient is prompted by a push notification if the application is not in the foreground, requesting the user to open the application and confirm their role in the trip - either a passenger or the driver. When the patient opens the application, they will be met with a dialog where they can select their role. The notification system is actuated by the Dart package Awesome Notifications. This initialization allows the application to remain as unobtrusive and as minimal maintenance as possible for daily use and regular driving. The driving data is then cleaned and stored on DataHub, where we can parse and format all statistics to display back to registered physicians. Figure 3 displays the overall system design.

those factors affect the understanding of glaucoma progression. Patients can also change their password and modify affiliated medical providers from this screen.

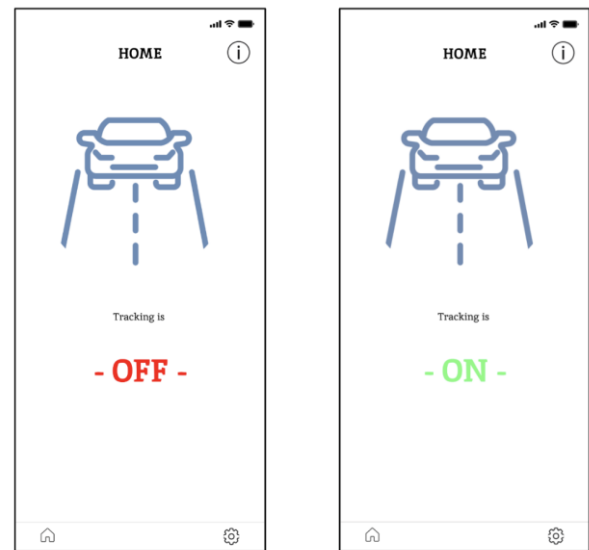


Fig. 4. Example landing screen for patients with tracking status.

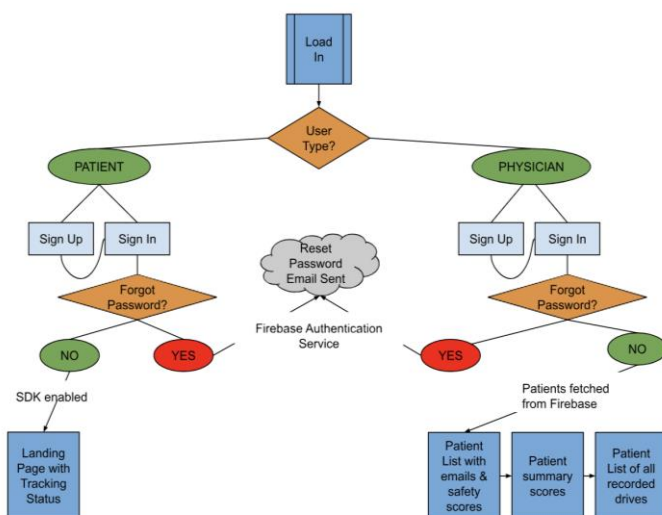


Fig. 3 Data flow diagram for overall system structure and screens from physician and patient interfaces.

The application currently provides a clean interface with a secure authentication system that allows patients and physicians to log in to their respective portals. The patient's landing screen simply informs the user whether the SDK is enabled or not. It does not reveal to the user their aggregated driving scores to prevent any intervention on the user's regular driving behavior. The landing screen is coupled with a tutorial catered to the patient's view.

Patients can also navigate to the settings page, where there is an embedded link in a tab to direct them to a form where they may request the deletion of any raw or processed data, a tab to view the application's privacy statement, an About Us tab to gain insights on our mission statement, and a tab to view and edit their profile. The Edit Profile screen will allow patients to add their gender and age if desired, as

The physician's landing page is composed of a clickable patient list that contains the patient's email and aggregated driving safety score, a search bar for swift patient lookup and options to sort the view by ascending safety scores or alphabetically by email address. The landing page also includes a tutorial addressing the physician's interface and driving metric explanation.

When a patient list item is clicked, more summary scores are displayed, including the total time driven, mileage, acceleration, cornering, braking, and phone usage scores. From this screen, physicians may click the 'View more driving analytics' button to navigate to a list of all trips driven by their patients and see all individual statistics and driving metrics for each trip. The settings screen for physicians mirrors the patients save for the request data form. The Edit Profile screen also has an additional text field where physicians may verify their accounts using their NPI if not previously completed during registration.

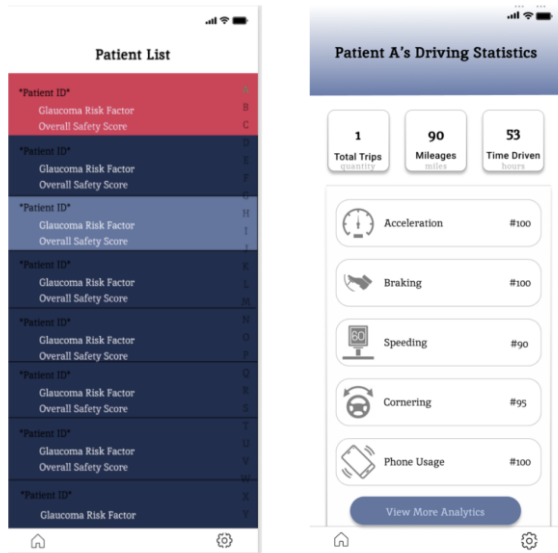


Fig. 5. Example landing screen for physicians with list of affiliated patients and safety score. Sample linking page with single test patient's summary scores, total mileage, trips taken and time driven.

C. Testing

After implementing the system, we conducted actuation tests to determine what factors most influenced the safety score through mundane day-to-day driving. We recruited four test subjects with no recorded or known medical history of glaucoma or other visual field impacts. There were three iPhone devices ranging from 2020 to 2023 and one Android device from 2023 and four different car models. Our objectives with this test were to certify automatic tracking, accurate driving event detection, and distinction between risky and safe driving. In total, twelve hours of simulated driving from three test drivers and approximately 30 hours of real driving data from four real drivers were collected.

IV. RESULTS AND DISCUSSION

With the real driving data we have obtained, we inputted each drive and corresponding drive events including counts of sudden acceleration, braking, rapid and abrupt cornering to determine the feature correlation and the most substantial scores in influencing the overall calculated safety score. We accomplish this by using Tableau [25] for data visualizations. We use the Pearson correlation coefficient for determining the relationship. Figure 6 posits that the acceleration, braking, and speeding are strongly positively correlated with the counts of sudden acceleration with values around 80, 85, and 90 respectively. The eco score fuel score also moderately have positive correlation at a coefficient at approximately 65. Braking along with inefficient eco score are most negatively correlated with the safety score with strong correlation coefficients less than -75. This may be intuitive, but it does compound the takeaway that typical, albeit not entirely safe or cautious drivers will not perform erratic cornering as glaucoma patients would which is reflected in the correlation map, we generated. It may also be deduced that drivers without glaucoma may occasionally accelerate or brake suddenly in circumstances signifying that a minimal amount should still be classified as mundane.

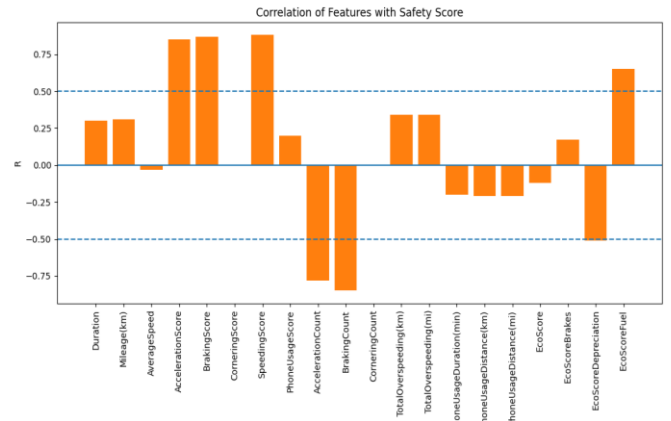


Fig. 6. Feature correlation chart using the driving event count and scores to analyze the importance of each factor in the safety score calculation.

Figures 8 and 9 represent visualizations of a single drive from an ideal driver and an unsafe driver in figures 9 and 10. The single drive with a safety score of 100 was from a simulated freeway drive of six minutes. There was a period of the drive where a speeding instance was recorded but did not affect the overall radar chart. This can be attributed to the speed needed on the freeway and a general tolerance of the length of speeding incidents. The drive extrapolated from the unsafe driving had a safety score of 53, primarily from their excessive speeding incidents, phone usage while driving, and their lurching maneuvers. The median score between all the non-simulated drivers was 72. From our testing, we determined that a score of 70 and upwards is an acceptable safety score. Driving events should still be assessed infrequently to see the repeatedly penalized events and evaluate the progression of visual field loss.

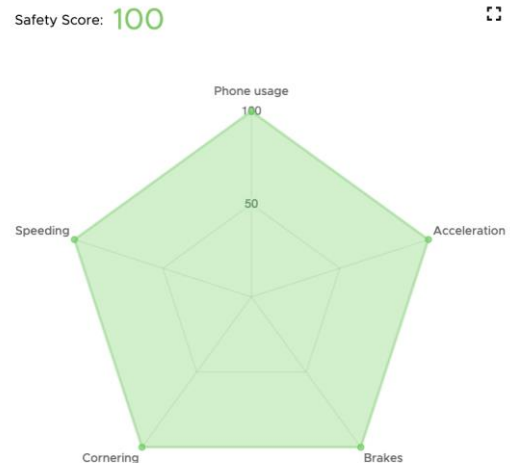


Fig. 7. Radar chart of a simulated freeway drive with an overall driving safety score of 100 representing an ideal trip.



Fig. 8. Timeline of all features from same drive as Fig. 7 of a perfect drive without phone use and devoid of dangerous maneuvers.

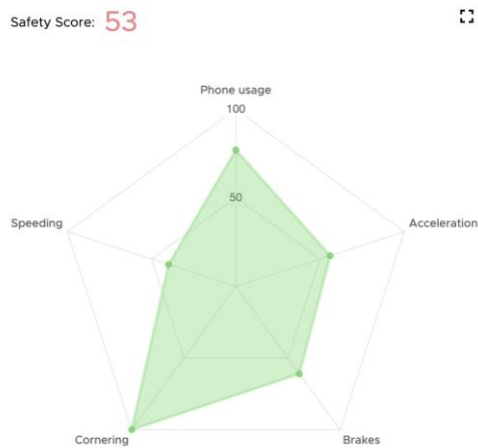


Fig. 9. Radar chart of an actual driver on the freeway with an overall safety score of 53 representing an unsafe trip.

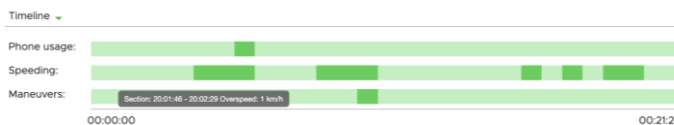


Fig. 10. Timeline of all features from same drive as Fig. 9 of an unsafe trip without repeated phone use, numerous unsafe speeding instances and multiple dangerous maneuvers.

Impact

To the authors' knowledge, this application is the first digital phenotyping software to monitor glaucoma through an individual's driving habits. The development of this application makes it easier for the individual to consistently monitor their glaucoma severity while reducing the need to regularly visit the optometrist to gain such insights. This application will also contribute insights to the relationship of driving habits and glaucoma severity through the vast array of driving data collected from its user base.

In both acting as a tool to predict glaucoma severity through the relationships between driving habits and glaucoma defined in literature and as a tool to gather further insights on the relationship between glaucoma severity and driving habits, this application is a dual-reinforcing tool.

In addition, most existing studies that analyze the impact of glaucoma on driving behavior compare drivers with and without glaucoma in heavily controlled environments (e.g., driving on the same road segment for the same short duration). Currently, there are few long-term real-world driving data sets for patients with glaucoma. In contrast, our application can longitudinally collect long-term driving data of glaucoma patients, providing further insights as to how driving is affected over time as glaucoma progresses.

Limitations

While the app has all the necessary components to achieve its primary purposes, there are several limitations and areas for improvement. First, while NPI verification is implemented, it does not act as a gatekeeper. That is, physicians without verified NPIs can still view patient statistics. Future iterations of the application should limit patient statistics to physicians with verified NPIs in order to ensure data security and patient safety.

Furthermore, the units of measurement for various metrics are not customizable (i.e., metric versus English system of measurements). To appeal to a global audience, the user should be able to customize their units of measurement in future versions of the application. Similarly, patient driving data is currently displayed in preset formats. Future iterations of the application should enable the user to customize the view of the data.

Moreover, the mobile application currently interfaces with an external data platform (i.e., Google Forms) allowing the user to view and export their driving data. Guaranteeing that the application is self-sufficient, robust, and secure, future versions of the application should integrate the data exportation form into the application.

Future Work

The current work establishes a platform whereupon driving data can be collected, and glaucoma can be monitored. Future stages of this study should first recruit a sufficient number of beta-testers to utilize the application in order to create a substantial collection of data. With a larger pool of subjects and varying degrees of glaucoma or susceptibility to developing glaucoma, the next crucial step is to identify the driving metrics that are highly correlated with the condition and establish relationships between the categories of data collected.

Taking advantage of the longitudinal nature of the data collection, data analysis should focus on temporal relationships, analyzing how driving behavior is affected over time. Given the expected quantity and types of data to be collected, future data analysis conducted through the application could verify some of the proposed relationships in the literature on a larger body of participants.

Finally, a machine learning algorithm should be implemented and integrated with the application to determine glaucoma severity through an individual's driving habits. The algorithm coupled with custom coefficients will optimize the scoring model. This is the final stage of the application and, when integrated, would make the application a valuable tool for monitoring glaucoma.

V. CONCLUSIONS

With a globally aging population and increasing dependence on driving, it is pertinent to gain more fine-grained insights into the impact of glaucoma on driving. By providing a platform to longitudinally collect driving data and monitor glaucoma, the application will contribute to this scarce market, helping to improve the ongoing quality of life of older adults and offering the potential for future research.

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