Journal of High School Science

A novel wearable device for the quantitative assessment of eye movement in Ocular Myasthenia Gravis (OMG): an exploratory engineering feasibility study

Gandhi P[1], Balasubramanian S[2]

Submitted: November 17, 2025, Revised: version 1, December 18, 2025, version 2, December 19, 2025, version 3, December 19, 2025, version 4, January 23, 2026, version 5, January 26, 2026, version 6, January 27, 2026, version 7, January 27, 2026, version 8, February 1, 2026
Accepted: February 2, 2026

Abstract
Ocular Myasthenia Gravis (OMG) is an autoimmune disorder characterized by fatigable weakness of the extraocular muscles. We conducted a non-clinical, exploratory engineering feasibility study to evaluate a low-cost, wearable eye-tracking device ("OMG-glasses") for quantitative characterization of ocular motility in OMG. To our knowledge, no wearable eye-tracking system has been specifically developed for OMG. Sixteen participants (eight clinically diagnosed OMG patients and eight healthy controls) performed a standardized gaze task while eye movements were recorded using a spectacle-mounted infrared camera. Custom software extracted trajectory-based ocular motility metrics. Compared with controls, OMG patients demonstrated significantly reduced horizontal (H) and vertical (V) gaze range and total path length, with vertical gaze being disproportionately reduced relative to horizontal gaze. The combination of a significant non–duration-normalized H:V ratio with a non-significant duration-normalized H:V ratio between the OMG and control groups indicated that this pattern itself may serve as an indicator of ocular motility deficit, rather than fatigue acting merely as a confounding factor. This pilot study has important limitations, including small sample size, unilateral assessment, and approximate calibration, and did not evaluate diagnostic accuracy. These findings demonstrate proof-of-concept differentiation of ocular motility patterns between known OMG patients and healthy controls and support further validation in larger, controlled studies.

Keywords
Ocular Myasthenia Gravis, Hardware, Wearable technology, Ocular motility, Repetitive Nerve Stimulation, Single-Fiber Electromyography, Oculomotor weakness, Acetylcholine receptors, Neuromuscular transmission

[1]Padmaja Gandhi, Navrachana International School, Vasna Bhayali Road, Vadodara, Gujarat 391410, India. padmajagandhi1113@gmail.com
[2]Corresponding author: Sankar Balasubramanian, Department of Mechanical Engineering, Indian Institute of Science (IISc), CV Raman Rd, Bengaluru, Karnataka 560012, India. sankarb@iisc.ac.in

https://doi.org/10.64336/001c.156159

1. Introduction

1.1. Myasthenia Gravis

Myasthenia Gravis (MG) is an autoimmune neuromuscular disorder characterized by fluctuating weakness of skeletal muscles that worsens with activity and improves with rest (1,2). The disease results from antibodies targeting components of the neuromuscular junction, most commonly acetylcholine receptors (AChR), leading to impaired neuromuscular transmission (2,3).

MG affects ~ 150-200 per million people worldwide, with a bimodal age distribution showing peaks in young adult women and in older men (1,4). Symptoms typically include ptosis (drooping eyelids), diplopia (double vision), facial weakness, difficulty in swallowing, and limb weakness. The hallmark feature is fatigability—muscle strength deteriorates with sustained or repeated use and recovers with rest (1,5).

The disease can remain localized to the ocular muscles (ocular MG) or progress to involve other muscle groups (generalized MG). ~ 50-60% of patients presenting with ocular symptoms progress to generalized disease within the first two years (4,6). Severe cases can lead to myasthenic crisis, a life-threatening condition involving respiratory muscle weakness requiring mechanical ventilation (7,8).

1.2. Ocular Myasthenia Gravis

Ocular Myasthenia Gravis (OMG) is a subtype where symptoms remain confined to the extraocular muscles, levator palpebrae superioris, and orbicularis oculi (1,2,5). The primary manifestations are ptosis and diplopia, which characteristically fluctuate throughout the day, typically worsening in the evening or with prolonged visual tasks (1,3).

The extraocular muscles are particularly susceptible to myasthenic weakness due to their unique physiological properties: they have a high firing frequency, lack the ability to recruit additional motor units, and contain a higher proportion of fast-twitch fibers (9). These characteristics make them vulnerable to fatigue from impaired neuromuscular transmission.

OMG represents ~ 15-20% of all MG cases at presentation (1,6). While some patients remain purely ocular, the majority progress to generalized disease. Early identification is clinically important as treatment can potentially slow or prevent this progression (6,10). The variable and fluctuating nature of symptoms, combined with the possibility of seronegative disease, makes OMG particularly challenging to diagnose (3,11).

1.3. Current methods for assessing OMG

Current assessment of OMG relies on clinical examination, serological testing, and electrodiagnostic studies, each with significant limitations (12). Clinical assessment involves evaluating ptosis, diplopia, and eye movement range, but is inherently subjective and lacks standardized quantification (13,14). The ice pack test, where cooling temporarily improves symptoms, is useful but is not specific to MG (15,16).

Serological testing for anti-AchR antibodies is

highly specific but has limited sensitivity in OMG, with ~ 50% of ocular-only patients being seronegative (11,17). Anti-MuSK and anti-LRP4 antibodies are found in some seronegative patients, but a significant proportion remain without detectable antibodies (11). Electrodiagnostic studies, including Repetitive Nerve Stimulation (RNS) and Single-Fiber ElectroMyoGraphy (SFEMG), can detect neuromuscular transmission defects (18,19). However, RNS has poor sensitivity in mild or purely ocular disease (30-50%), while SFEMG, though more sensitive (80-90%), is technically demanding, uncomfortable, and not universally available (20-23).

These limitations create diagnostic delays averaging 1-2 years from symptom onset (3). The lack of objective, quantitative, and accessible methods for assessing ocular motility deficits in OMG represents an unmet clinical need that motivated the development of the OMG-glasses as a potential characterization tool.

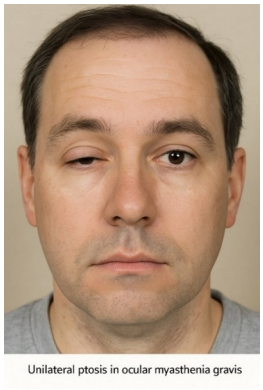

Figure 1. Unilateral ptosis in OMG

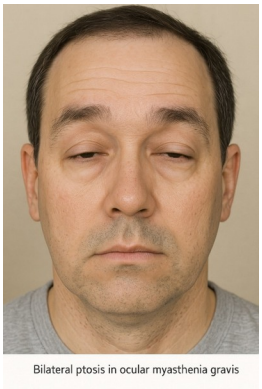

Figure 2. Bilateral ptosis in OMG

1.4. The critical challenge of early characterization

The early and accurate characterization of OMG presents a considerable challenge for clinicians (1,3). The fluctuating nature of ptosis and diplopia is a primary complicating factor. A patient may report significant double vision in the evenings, but their eye movements may appear entirely normal during a morning appointment. This can lead to the symptoms being dismissed or attributed to other causes, such as simple fatigue or refractive errors.

Furthermore, the initial stages of OMG can be subtle. They can be mistaken for other neurological or ophthalmological conditions. The diagnostic process often involves a combination of clinical evaluation and specific tests. A simple in-clinic test, called the ice pack test, can be indicative (15,16). Placing an ice pack on a drooping eyelid for a few minutes can temporarily improve the ptosis, as cooling improves neuromuscular transmission (16,19). However, this test is not definitive. More specific diagnostic methods include blood tests to detect the presence of anti-AChR antibodies (11,17). While a positive test is highly specific for MG, about 50% of patients with purely

ocular symptoms may not have these detectable antibodies in their blood (4,17). This condition is referred to as seronegative OMG. It makes a blood-based diagnosis challenging for this subset of patients.

Another characterization tool is electrodiagnostic, such as RNS (20,21). This test assesses for a decline in muscle response with repeated electrical stimuli. However, in early or mild OMG, the RNS test may not be sensitive enough to detect abnormalities (20,21). These diagnostic ambiguities can lead to significant delays in confirming the condition (3,19).

1.5. The risk of progression to Myasthenic crisis

The importance of early characterization is underscored by the natural course of the disease. OMG is not merely a condition affecting vision; it is often the precursor to a more severe, generalised form of the disease. It is estimated that ~ 60% of patients who initially present with only ocular symptoms will progress to Generalised Myasthenia Gravis (GMG) (4,6). This progression typically occurs within the first one to two years after the onset of symptoms.

In GMG, the muscle weakness spreads beyond the eyes. It can affect the bulbar muscles (muscles of the mouth and throat), limb muscles, and, most critically, the respiratory muscles. Weakness in the bulbar muscles can cause difficulty in chewing, swallowing (dysphagia), and speaking (dysarthria). Limb weakness can make it difficult to perform daily activities such as climbing stairs, lifting objects, or even combing one's hair. The most severe complication of Myasthenia Gravis is the myasthenic crisis (7,8). This is a life-threatening medical emergency. It occurs when the muscles that control breathing, primarily the diaphragm and intercostal muscles, become too weak to maintain adequate ventilation. The patient experiences respiratory distress and may require mechanical ventilation to support their breathing. A myasthenic crisis can be triggered by infections, surgery, or other stressors (7,8). Prompt recognition and intervention are vital to prevent respiratory failure. Therefore, diagnosing the condition in its initial ocular stage is of paramount importance. Early treatment can potentially reduce the risk or severity of generalisation and prevent life-threatening crises.

1.6. A new paradigm: quantifying ocular motility for characterization

Given the limitations of current diagnostic methods for early-stage OMG, there is an unmet need for a more objective and sensitive tool (24-26). The restricted and fatigued movement of the eyes in OMG provides a potential biomarker that has not been fully exploited. While clinicians observe eye movements, this assessment is largely subjective and qualitative. A quantitative approach, which measures the precise range and characteristics of eye motion, could provide a more reliable diagnostic indicator (12,13,27).

The hypothesis of this research is that the trajectory of eye movement can be numerically analyzed (25,28). This analysis can reveal patterns that are distinct in OMG patients compared to healthy individuals. Healthy individuals can typically move their eyes smoothly to their full rotational extent (14,29).

In contrast, patients with OMG are expected to exhibit a restricted range of motion (5,13). Their eye movements may also be saccadic (jerky) or show a progressive decline in range during sustained tasks. By capturing these subtle differences, a quantitative method could detect the disease in its early stages (10,30). This would be particularly valuable for seronegative patients or in those with ambiguous electrodiagnostic results (11,18,22).

1.7. The OMG-glasses: a wearable solution

To address this diagnostic gap, we have developed a novel, low-cost, wearable device named "OMG-glasses". The device is designed as a non-invasive tool for ocular motility characterization. It is built upon a standard spectacle chassis, making it familiar and easy for patients to wear. The core of the device is an inward-facing infrared (IR) camera. This camera is mounted on the frame and positioned to continuously record the movements of the user's eye.

The camera is a compact 8-megapixel module equipped with infrared illuminators. This allows for clear imaging of the pupil even in varying ambient light conditions. The camera is connected to an ESP32 S3 microcontroller, a small but powerful chip with built-in Wi-Fi capabilities. The microcontroller processes the camera feed and wirelessly transmits the video stream to a nearby laptop or computer. This allows for real-time monitoring and recording of the patient's eye movements during a structured examination. The recorded video can then be subjected to computational analysis to extract quantitative data.

The OMG-glasses are designed to be a practical tool for the clinical setting. They offer a method to capture objective data on ocular motility that is easy to administer and repeatable. The device can track the progression of the disease over time and assess the response to treatment.

1.8. Objectives of the study

The primary aim of this non-clinical engineering feasibility study was to design, build, and conduct a proof-of-concept evaluation of whether the OMG-glasses could detect differences in ocular motility patterns between known OMG patients and healthy controls. This study did not evaluate diagnostic ability.

Specific objectives were: [1] To construct a functional prototype: This involved integrating the IR camera, microcontroller, and power source into a wearable and comfortable spectacle frame. [2] To develop a data collection protocol: A standardised procedure was created to guide participants through a set of specific eye movements, ensuring consistency across all tests. [3] To conduct a pilot study: Eye movement data were collected from a control group of healthy, able-bodied individuals and a patient group of individuals previously diagnosed with OMG. [4] To analyze and compare the data: The recorded videos were processed to generate eye movement trajectory graphs. These graphs were then quantitatively and qualitatively compared between the two groups to identify significant, measurable differences. [5] To evaluate differentiation capability: Based on the analysis, the study aimed to provide a preliminary assessment of the device's ability to distinguish ocular motility

patterns between known OMG patients and healthy individuals.

2. Materials and Methods

This section provides a detailed account of the materials used and the procedures followed in this study. It covers the design and architecture of the diagnostic system. It also describes the fabrication of the OMG-glasses prototype. Finally, it outlines the methodology of the experimental study, including participant recruitment, data collection, and analysis techniques.

2.1. System architecture

The diagnostic system developed for this research was composed of three primary modules. These were the Data Acquisition Module, the Data Transmission and Recording Module, and the Data Processing Module. The overall architecture was designed for a seamless flow of information. The flow began with capturing eye movement and ended with quantitative graphical analysis. The complete architecture is shown in Figure 3.

The Data Acquisition Module was the core hardware component of the OMG-glasses. This wearable device was responsible for continuously imaging the participant's eye during the experimental task. It captured the raw visual data necessary for the analysis. The Data Transmission and Recording Module consisted of two parts. The OMG-glasses used a built-in Wi-Fi antenna to wirelessly stream the captured video feed. A standard laptop computer, acting as a base station, received this feed. The laptop ran Open Broadcaster Software (OBS) Studio. This software is configured to capture the wireless video stream and record it as a standard digital video file (MP4). The Data Processing Module was a custom-written software program. It was coded using the Python programming language. This program used the recorded MP4 video file as its input. It employed computer vision algorithms to track the pupil's movement frame-by-frame. The output of this module resulted in a two-dimensional trajectory graph. This graph visually represented the path of the participant's eye movement. It also included key quantitative metrics.

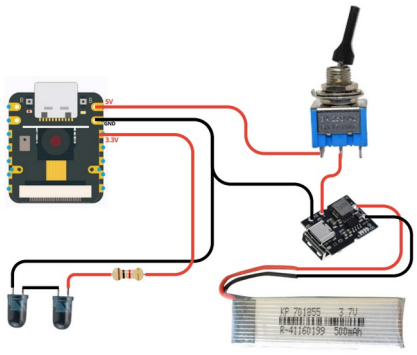

Figure 3. A block diagram illustrating the glasses mounted hardware. IR LEDs' (bottom left), Camera module (top left) comprised the imaging system. A microprocessor with WiFi connectivity and battery (middle and bottom right) comprised the data acquisition, transmission and power system.

2.2. The OMG-glasses: hardware prototype

A functional hardware prototype, named the OMG-glasses, was designed and fabricated for this study as shown in Figures 4-6. The device was constructed using commercially available electronic components. The design prioritised functionality, ease of use, and participant comfort.

2.2.1. *Component selection and description*

The selection of each component was based on its specific function, small form factor, and low power consumption. [1] Spectacle Frame: A standard, non-prescriptive spectacle frame was used as the chassis for the device. The frame provides a familiar and stable platform to mount the electronic components. It ensured that the device could be worn comfortably by participants. [2] Microcontroller: The brain of the device consisted of a XIAO ESP32 S3 Sense board. This is a very small microcontroller unit that integrates a processor, Wi-Fi connectivity, and a camera interface. Its small size is ideal for a wearable application. The built-in Wi-Fi capability was crucial for wirelessly transmitting the video feed, thus eliminating the need for cumbersome cables. [3] Imaging Module: An OV2640 camera module was selected for image capture. This is a 2-megapixel camera, which is sufficient for the task of pupil tracking. Importantly, the camera was modified for this application. The internal infrared (IR) filter was carefully removed from the lens assembly. This modification allows the camera sensor to detect infrared light, which was essential for our illumination method. [4] Illumination System: Two 850nm infrared Light Emitting Diodes (LEDs) were integrated into the device. Human eyes are not sensitive to light at this wavelength. This meant that the LEDs could brightly illuminate the eye without causing any visible glare or discomfort to the participant. This consistent illumination ensured reliable pupil detection under various ambient lighting conditions. [5] Power System: The device was powered by a portable and rechargeable system. A 3.7V, 500mAh Lithium-Polymer (Li-Po) battery was chosen for its high energy density and light weight. The battery was connected to a Type-C USB 5V 2A Boost Converter module. This module served two purposes. It stepped up the battery's voltage to a stable 5V required by the microcontroller. It also provided a standard USB Type-C port for easy recharging of the battery. [6] Control Switch: A simple miniature toggle switch was included in the circuit. This allowed the device to be easily powered on and off by the experimenter.

Figure 4. Hardware prototype of the OMG-glasses

2.2.2. *Fabrication and assembly*

The components were carefully assembled onto the spectacle frame to create the final prototype. The XIAO ESP32 S3 board was mounted on the side arm of the frame. The OV2640 camera module was positioned on the frame near the nose bridge. It was angled inwards to have a clear and direct view of the participant's right eye. The two infrared LEDs were placed on the upper rim of the frame to provide even illumination.

Figure 5. Frontal view of the fully assembled OMG-glasses prototype

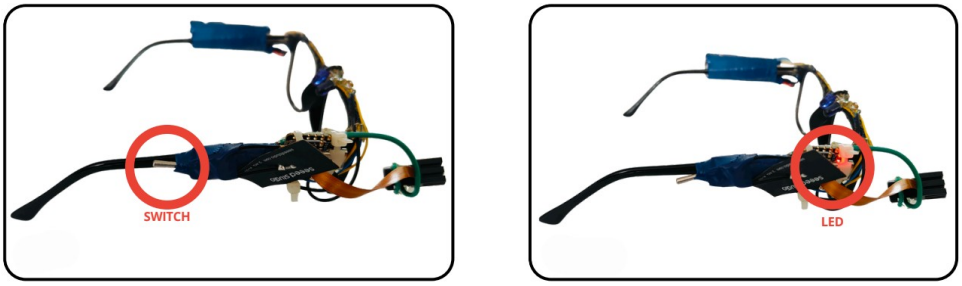

Figure 6. A side-view of the OMG-glasses prototype, showing the mounting of the microcontroller, battery, power module, LED and switch

The battery and the power converter module were secured to the other side arm of the spectacles. All components were interconnected using thin, flexible wires. The connections were made according to the electronic schematic diagram. To protect the circuitry and secure the components in place, electrical tape and a strong adhesive were used. The final prototype was a self-contained, wearable unit.

2.3. Experimental study

A pilot experimental study was conducted to collect preliminary data. The study was designed to compare the eye movement patterns of healthy individuals with those of patients diagnosed with OMG. The UI developed for collecting the data is shown in Figure 7.

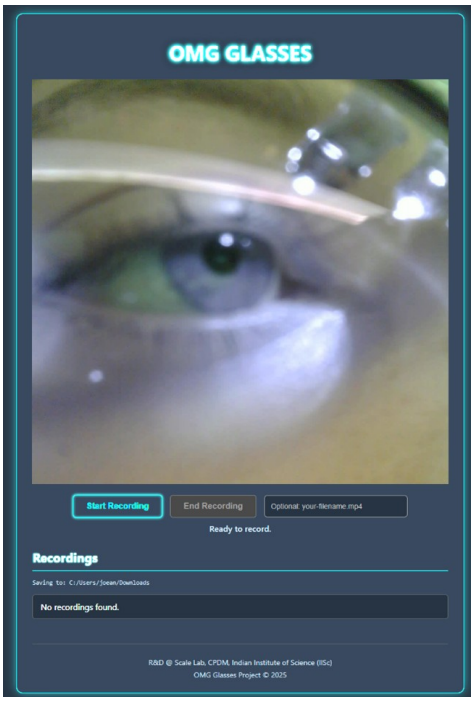

Figure 7. User Interface of the application for recording using OMG-glasses.

2.3.1. *Participant recruitment*

A total of sixteen participants were included in this study. They were divided into two groups of eight. Group A (Control Group): This group consisted of eight healthy, able-bodied volunteers. The inclusion criteria were, be of age between 20 and 50 years and have no history of any neurological or ophthalmological disorders. Participants who wore corrective lenses for vision were included, but the experiment was conducted without their personal spectacles with the corrective lenses. Group B (Patient Group): This group consisted of eight patients who had been previously diagnosed with OMG by qualified neurologists. Characterization was based on standard clinical criteria including characteristic symptoms (ptosis and/or diplopia), positive ice pack test, and/or serological testing for anti-AChR receptor antibodies. The patients were volunteers and were informed about the nature of the study.

Informed consent was obtained from all participants before their inclusion in the study. The study protocol was designed to be non-invasive and adhered to ethical principles. The privacy and confidentiality of all participants were strictly maintained. Each participant was assigned an anonymous identifier (e.g., P1, P2, …. P8 for control participants and O1, O2, …..O8 for OMG patients) for data identification purposes.

2.3.2. *Experimental setup*

The experiment was conducted in a quiet indoor room with consistent artificial lighting. This was done to minimise environmental distractions and minimize variations in ambient light. Each participant was seated comfortably in a chair. A laptop computer was placed on a table ~ 1.5 metres in front of the participant. The laptop was used by the experimenter to monitor and record the video stream from the OMG-glasses. The experimenter stood next to the laptop to guide the participant through the eye movement task. The setup is shown in Figure 8.

Figure 8. Experimental testing environment.

2.3.3. *Data collection protocol*

A standardised protocol was followed for data collection from every participant. This ensured consistency and comparability of the data across all tests.

2.3.3.1 Briefing and preparation

The participant was first briefed about the procedure. The experimenter explained the eye movement task they needed to perform. The OMG-glasses were then carefully placed on the participant's face. The fit was adjusted for comfort and to ensure that the camera had an unobstructed view of the right eye.

2.3.3.2 Device activation and streaming

The experimenter turned on the OMG-glasses using the toggle switch. A dedicated Wi-Fi network with the SSID "OMGglass" and password "omgglass" was created using a mobile hotspot. The OMG-glasses automatically connected to this network. On the laptop, OBS Studio was launched. A "Browser" source was added in OBS, and the URL http://eyecam.local/mjpeg/1 was entered. This initiated a live video stream from the glasses to the laptop screen.

2.3.3.3 Eye movement task

The core of the protocol was a guided eye-tracking task. The participant was instructed to keep their head perfectly still throughout the task. They were asked to focus their gaze only on the experimenter's index finger, which served as a visual target. The experimenter then moved the target in a predefined pattern; [1] Start:The target was held stationary at the centre of the participant's visual field for a few seconds. [2]

Horizontal Movement: The target was moved slowly towards the participant's far left, then back to the centre, and then slowly towards the far right. It was then returned to the centre. [3] Vertical Movement: From the centre, the target was moved slowly upwards to the highest point of the participant's vertical gaze, then back to the centre. It was then moved slowly downwards to the lowest point of their gaze. [4] End: The target was finally returned to the central position.

2.3.3.4 Recording and data storage

The experimenter started the recording function in OBS Studio immediately before the eye movement task began. The entire sequence of eye movements was recorded as a single video. Once the task was completed, the recording was stopped. The resulting MP4 file was saved in the laptop's hard drive. The file was named using the participant's anonymous identifier to ensure proper data management.

2.3.4. *Ethical considerations*

The study was conducted as a non-clinical, exploratory engineering feasibility study to assess the technical capability of the device under the CreatED high school research program. It was not designed or intended as a clinical diagnostic validation study. Formal Institutional Review Board (IRB) approval was therefore not obtained prior to study initiation. However, the study was conducted under the supervision of a clinical doctor, research supervisor, the parents of the high school author and the head of CreatED**.**

2.3.4.1 Infrared safety assessment

The device employed two 850nm infrared LEDs for eye illumination. At this wavelength and the low power used (<50mW total), with brief exposure duration (<1 minute per testing session), the infrared exposure fell within the exempt risk group (RG0) per IEC 62471 (33) photobiological safety standards for lamps and lamp systems. The infrared illumination intensity was comparable to or less than that of standard commercial webcams, television remote controls, and proximity sensors commonly used in consumer electronics. No participant reported any discomfort during or after testing.

2.3.4.2 Informed consent

Written informed consent was obtained from all participants prior to their inclusion in the study. Participants were informed about the nature of the research, the procedures involved, and their right to withdraw at any time without consequence. For OMG patients, consent was obtained in coordination with their treating physicians.

2.3.4.3 Data privacy safeguards

Only eye movement videos were recorded; no facial images were captured. All data were immediately anonymized using participant codes (P1-P8 for controls, O1-O8 for patients). Raw video recordings were stored on encrypted local storage and deleted after trajectory data extraction. Only anonymized trajectory data were retained for analysis. No personally identifiable information was included in the dataset.

2.4. Data processing and analysis

The collected video files were subsequently processed to extract ocular motility quantitative

data.

2.4.1. *Pupillary tracking and trajectory generation*

A custom computer program, written in the Python programming language, was developed for data analysis. The program was designed to automate the extraction of eye movement data from the recorded videos. For each video file, the program performed the following steps, [1] It loaded the video and processed it frame by frame. [2] In each frame, it used a computer vision algorithm to detect the circular shape of the pupil. [3] It calculated the geometric center of the detected pupil. The (x,y) pixel coordinates of this center were recorded for each frame. Pixel coordinates were converted to ~ gaze angles using geometric transformation based on the camera's known field-of-view (~ 66°) and image resolution. The relationship assumed a linear mapping within the central visual field. [4] This sequence of coordinates, representing the pupil's position over time, was then used to generate a trajectory path.

2.4.2. *Quantitative analysis and graph plotting*

The program used the trajectory data to generate a two-dimensional plot. The horizontal and vertical displacement of the pupil were plotted on the X and Y-axis respectively. The axes were calibrated and represented in degrees of gaze angle. This processing created an intuitive visual representation of the eye's complete range of motion during the task.

In addition to the plot, the program calculated several quantitative metrics from the trajectory data, [1] Horizontal Range: The maximum angular displacement achieved on the horizontal axis (left to right), [2] Vertical Range: The maximum angular displacement achieved on the vertical axis (up to down), [3] Total Path Length: The cumulative length of the trajectory path, representing the total distance the eye travelled.

These metrics, along with the trajectory graph, were generated for each participant. The data from the control group was then compared with the data from the patient group to identify characteristic differences.

2.4.3. *Statistical analysis*

Statistical analysis was performed to compare quantitative metrics between the control and patient groups. Given the small sample size ($n = 8$ per group) and the non-normal distribution of some variables (Shapiro-Wilk test: Vertical Range in OMG group, $W = 0.732$, $p = 0.005$), non-parametric methods were employed.

Descriptive statistics are reported as median with interquartile range (IQR). Additionally, 95% confidence intervals were calculated using bootstrap resampling with 10,000 iterations. Between-group comparisons were performed using the Mann-Whitney U test with Bonferroni correction for multiple comparisons (4 tests; adjusted $\alpha = 0.0125$).

Effect size was quantified using Cliff's delta (δ), which is appropriate for non-parametric ordinal data. Cliff's delta ranges from -1 to +1, with $|\delta| < 0.147$ indicating negligible effect, $|\delta| < 0.33$ small effect, $|\delta| < 0.474$ medium effect, and $|\delta| \geq 0.474$ large effect. A post-hoc power analysis was performed based on observed effect sizes. For an *a priori* power analysis with $\alpha = 0.05$,

power = 0.80, and a large effect size (δ = 0.474), the minimum required sample size was calculated at ~ 26 per group. The current pilot study (n = 8 per group) was adequately powered to detect the (fortuitous) very large effects observed (δ > 0.78 for all motility metrics) but would be underpowered to detect smaller effects.

2.4.4. *Pixel-to-Degree calibration and measurement uncertainty*

The conversion of pupil position from pixel coordinates to gaze angle in degrees was performed using a geometric ~ based on the OV2640 camera's field of view (~ 66°) and image resolution (640 × 480 pixels at VGA mode). This yielded an ~ conversion factor of 0.103°/pixel.

The accuracy of video-based infrared eye tracking systems has been extensively studied. According to recent literature (31,32), interpolation-based eye tracking methods using infrared illumination typically achieve accuracies in the range of 0.5° to 1.5° depending on system configuration and calibration quality. For our low-cost prototype without formal calibration against a gold-standard system, we conservatively estimated a measurement uncertainty of ±1.5°.

To assess whether this uncertainty affected the validity of our findings, we compared the observed between-group differences to the measurement uncertainty, Horizontal Range difference: 20.6° (signal-to-uncertainty ratio: 13.7×); Vertical Range difference: 25.7° (signal-to-uncertainty ratio: 17.1×); Total Path Length difference: 80.9° (signal-to-uncertainty ratio: 53.9×). The observed differences between groups were 14 to 54 times larger than the estimated measurement uncertainty, supporting the validity of our findings despite the lack of formal calibration.

It should be noted that pixel-to-degree mapping in patients with OMG may be affected by fatigue, which is characteristic of the disease. To address this concern, we performed an additional analysis normalizing measurements by session duration (see Section 3.1.4). All angular values reported in this study are ~ estimates based on geometric conversion from pixel coordinates. These values should not be interpreted as precise clinical measurements. The emphasis should be placed on relative differences between groups rather than absolute angular values.

3. Results and Discussion

This section presents the findings of the experimental study. It begins by describing the qualitative and quantitative data obtained from both the control and patient groups. A detailed discussion then follows, interpreting these results in the context of OMG. The section concludes by acknowledging the limitations of this study and proposing directions for future research.

3.1. Results

The eye movement data collected from all sixteen participants were processed. The analysis yielded distinct and measurable differences between the healthy control group (Group A) and the OMG patient group (Group B). The results are presented using trajectory graphs and a summary of quantitative metrics as

shown in Figure 9 and 10 and Table 1 respectively.

3.1.1. *Eye movement patterns in the control group (Group A)*

The participants in the healthy control group demonstrated a consistent and predictable pattern of eye movement. They were able to follow the visual target smoothly and accurately throughout the entire task.

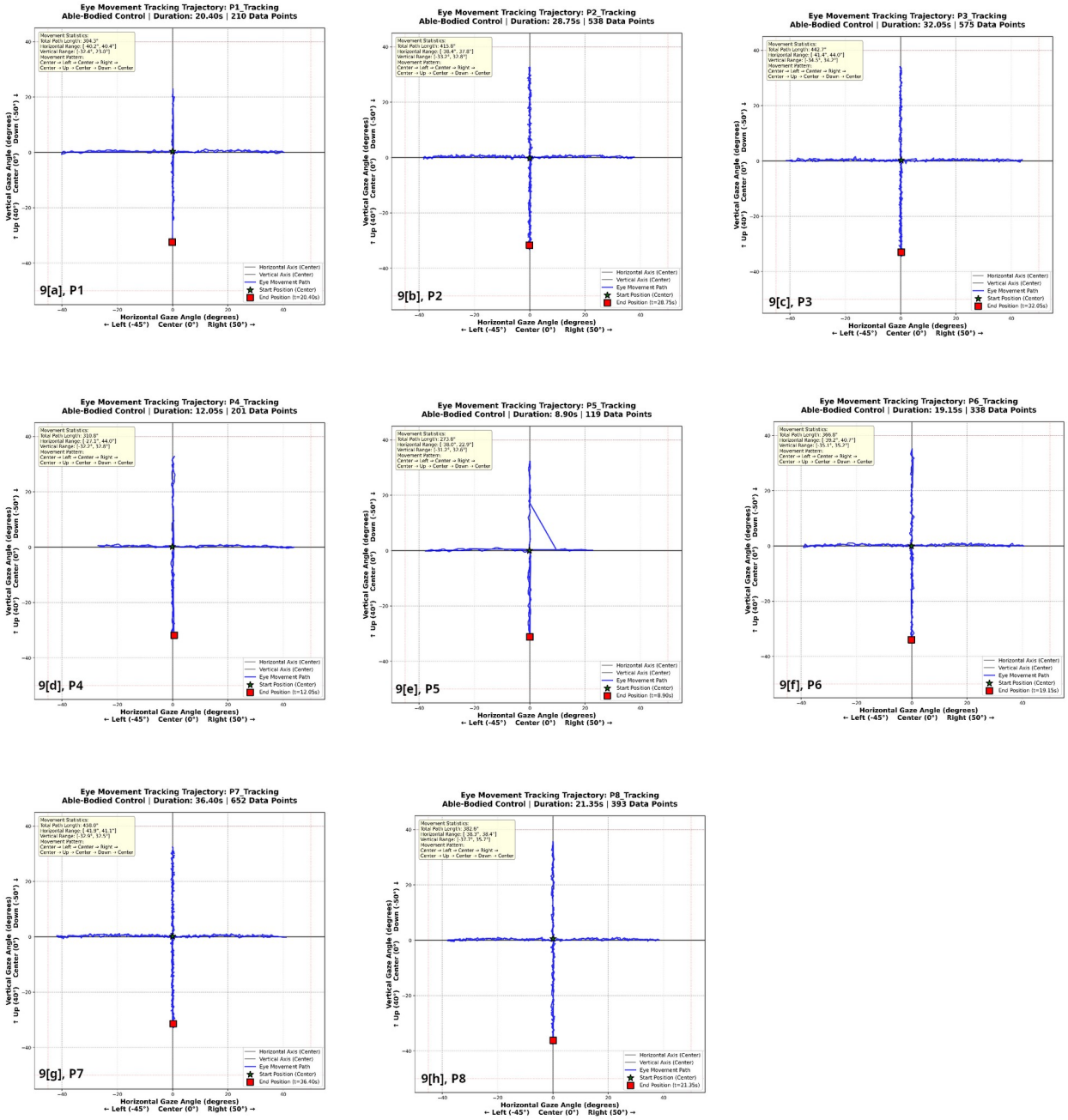

Figure 9. a to **h**. The eye movement trajectory graphs for healthy control participants (P1 to P8)

Quantitatively, the control participants exhibited a large range of motion. The horizontal gaze angles were typically > ±35 degrees. The vertical gaze angles also showed a wide range, often reaching the limits of the measurement scale. The total path length, which is a measure of the total excursion of the eye, was consistently high for this group. These numerical values correspond to the extensive trajectories seen in their graphs (Figure 9)

3.1.2. *Eye movement patterns in the OMG patient group (Group B)*

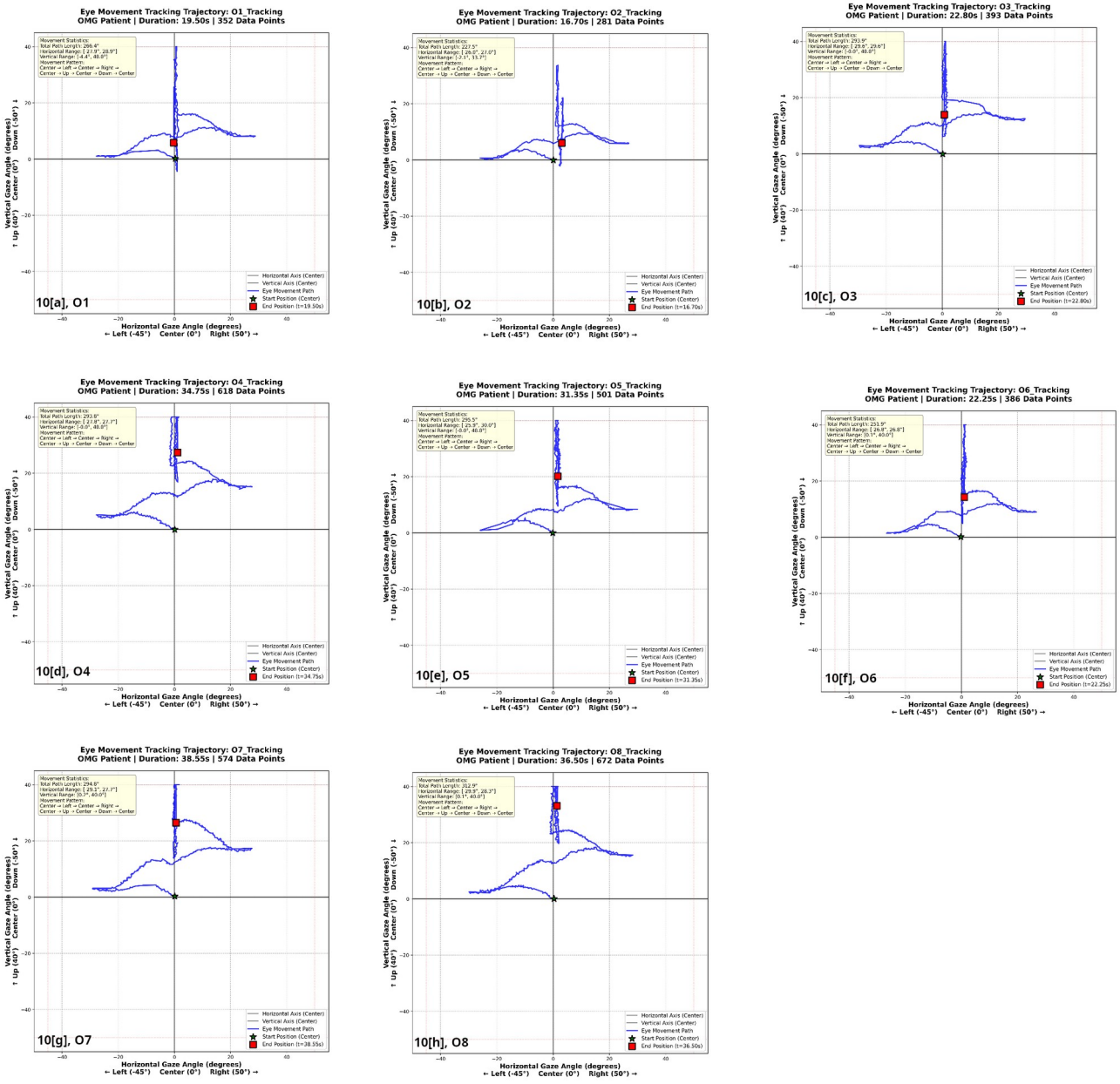

Figure 10. a to **h**. The eye movement trajectory graph for OMG patients (O1 TO O8)

In contrast, the participants in the OMG patient group showed markedly different eye movement patterns. Their ability to follow the visual target was visibly impaired. The trajectory graphs for this group are characterized by their restricted and irregular nature (Figure 10).

The classic cross shape observed in the control group was absent in the patient data. Instead, the trajectories were compressed and often incomplete. The extent of eye movement was significantly reduced in one or more directions. For example, a patient might show a reasonable horizontal range but a severely limited upward gaze. The paths traced by the eye were often erratic and non-linear. They showed deviations and corrective saccades, which appeared as jagged or wavy lines on the graph. This reflects the underlying muscle weakness affecting the ability to achieve a full range of motion.

The quantitative data for the patient group reinforced these visual observations. Both the horizontal and vertical ranges of motion were found to be smaller than those of the control group. The total path length of the eye's movement was also significantly lesser. This indicated that the overall capacity for eye movement was reduced in these patients. This reduction reflected a direct numerical correlate of the muscle weakness caused by the disease.

3.1.3. *Comparative analysis*

A direct comparison of the quantitative metrics found a measurable separation between the two groups. A summary of the values for key parameters is presented in Table 1.

Table 1. Quantitative results for the Able Bodied (AB) control group and the OMG patient group.

Subj	Duration (s)		Path length (degrees)		Horizontal Range (degrees)		Vertical Range (degrees)	
	AB	OMG	AB	OMG	AB	OMG	AB	OMG
1	20.40	19.50	304.3	266.4	−40, 40	−27, 28	−32, 23	−4, 40
2	28.75	16.70	415.8	227.5	−38, 37	−26, 27	−33, 33	−2, 33
3	32.05	22.80	442.7	293.9	−41, 44	−29, 29	−34, 34	−0, 40
4	12.05	34.75	310.8	293.8	−27, 44	−28, 27	−32, 33	−0, 40
5	08.90	31.35	273.8	295.5	−38, 23	−26, 30	−31, 33	−0, 40
6	19.15	22.25	366.8	251.9	−39, 40	−27, 26	−35, 35	−0, 40
7	36.40	38.35	458.0	294.8	−42, 41	−29, 27	−33, 32	−0, 40
8	21.35	36.50	382.6	312.9	−38, 38	−30, 28	−37, 36	−0, 40
Mean	**22.38**	**27.78**	**369.35**	**279.59**	**−38, 38**	**−28, 28**	**−33.7, 32**	**−0.8, 39**
SD	**8.90**	**7.87**	**63.61**	**26.59**	**4.3, 6.3**	**1.4, 1.1**	**1.9, 3.7**	**1.5, 2.1**

As Table 1 shows, the average range of motion and total path length for the OMG patient group is lower than for the healthy control group. This quantitative difference provides objective

evidence that can be used to distinguish between the two populations based on their ocular motor performance.

Table 2. Statistical comparison between Able-bodied control and OMG patient groups

Metric	Control (n = 8)	OMG (n = 8)	U	p-value	Cohen's d
Total Path Length (°)	369.35 ± 68.00	279.59 ± 28.42	57.0	0.007**	1.72
Horizontal Range (°)	76.72 ± 7.77	56.10 ± 2.09	64.0	< 0.001***	3.63
Vertical Range (°)	66.00 ± 5.33	40.02 ± 2.30	64.0	< 0.001***	6.33
Duration (s)	22.38 ± 9.52	27.77 ± 8.42	20.0	0.234	-0.60

Values are Mean ± SD. Mann–Whitney U test used for between-group comparisons. ***p*** < 0.01, ***p*** < 0.001

As shown in Table 2, The Mann-Whitney U tests found statistically significant differences between the two groups for the Total Path Length (U = 57.0, p = 0.007), Horizontal Range (U = 64.0, p < 0.001), and Vertical Range (U = 64.0, p < 0.001). All three metrics showed large effect sizes (Cohen's d > 0.8), indicating significant differences in ocular motility between known OMG patients and healthy controls. The duration of the task did not differ significantly between groups (p = 0.234).

Table 3. Statistical comparison between control and OMG groups using non-parametric methods

Metric	Control (n = 8) Median (IQR)	OMG (n = 8) Median (IQR)	U	p-adj	Cliff's δ	Effect
Total Path Length (°)	374 (309–422)	294 (262–295)	57	0.028*	0.78	Large
Horizontal Range (°)	78 (75–81)	56 (55–57)	64	0.004**	1.00	Large
Vertical Range (°)	65 (64–69)	40 (40–40)	64	0.003**	1.00	Large
Duration (s)	20.9 (17.4–29.6)	27.1 (21.6–35.2)	20.0	0.938	–0.38	Medium

Mann–Whitney U test with Bonferroni correction for multiple comparisons (4 tests). Significance levels: ***p*** < 0.05, ****p*** < 0.01, *****p*** < 0.001 (adjusted p-values shown). *Cliff's δ interpretation:* |δ| < 0.147 negligible, < 0.33 small, < 0.474 medium, ≥ 0.474 large.

3.1.4. *Horizontal-to-Vertical ratio analysis*

To investigate potential fatigue-related confounding effects, we calculated the ratio of horizontal to vertical range (H:V ratio) for each participant and analysed this metric both in raw form and normalized by session duration.

As shown in, and calculated from, Table 4, the raw H:V ratio showed a statistically significant difference between groups (U = 6.0, $p = 0.005$, Cliff's δ = -0.81), with OMG patients demonstrating proportionally greater restriction in vertical relative to horizontal gaze. However, when the H:V ratio was normalized by session duration as a surrogate for fatigue effects, this difference was no longer significant (U = 35.0, $p = 0.798$, Cliff's δ = 0.09, negligible effect).

Table 4. Individual participant H:V ratios and duration-normalized values

Control Group			OMG Patient Group		
ID	**H:V Ratio**	**Norm (s^{-1})**	**ID**	**H:V Ratio**	**Norm (s^{-1})**
P1	1.455	0.0713	O1	1.279	0.0656
P2	1.155	0.0402	O2	1.480	0.0886
P3	1.243	0.0388	O3	1.480	0.0649
P4	1.094	0.0908	O4	1.387	0.0399
P5	0.955	0.1073	O5	1.397	0.0446
P6	1.137	0.0594	O6	1.340	0.0602
P7	1.269	0.0349	O7	1.420	0.0370
P8	1.045	0.0489	O8	1.450	0.0397
Median	**1.146**	**0.0541**	**Median**	**1.409**	**0.0524**

3.2. *Discussion*

The results of this pilot study suggest that the OMG-glasses can capture and quantify the defining characteristics of impaired eye movement in OMG. The measurable distinction between the trajectory patterns of healthy individuals and OMG patients form the basis for this discussion. This study did not evaluate diagnostic ability, sensitivity, or specificity. The findings demonstrate proof-of-concept differentiation between known groups, not diagnostic capability.

The loss of statistical significance after duration normalization indicated that fatigue was likely a major contributor to the observed between-group differences, rather than a secondary effect. The observed differences in ocular motility likely reflected combined effects of underlying muscle weakness and fatigability, both of which are characteristic features of OMG. Fatigability may hence be used as a differentiation contributor between the two groups (see below) rather than merely being reported as a confounding factor.

Significance in non-duration normalized H/V ratio, when combined with non-significance in the normalized H/V ratio, may – together – itself be taken as evidence of ocular motility affective conditions resulting from ocular muscle weakening. In other words, the combination of a significant non–duration-normalized H:V ratio with a non-significant duration-normalized H:V ratio may itself be taken to be a specific differentiator for OMG. Rather than indicating a stable, direction-specific ocular motility/fatigue bias, this pattern is consistent with a time-dependent, fatigable neuromuscular impairment in which apparent vertical–horizontal asymmetries emerge during task performance but diminish when scaled to exposure duration. This interpretation emphasizes the dynamic nature of oculomotor weakness in OMG, rather than a fixed anisotropy of muscle involvement. While speculative, this raises the hypothesis that the sensitivity of directional ratios to duration normalization may differ between neuromuscular junction disorders such as OMG and conditions characterized by more fixed mechanical or neurogenic constraints (e.g., thyroid eye disease or cranial nerve palsies), a

possibility that warrants explicit testing in future disease-comparator cohorts using the OMG-glasses.

3.2.1. *Interpretation of the observed trajectory patterns*

The fundamental difference between the two groups lies in the integrity of their neuromuscular junctions. In the healthy control participants, the transmission of acetylcholine is efficient. This allows their extraocular muscles to receive uninterrrupted and unattenuated signals from the nerves, resulting in strong, sustained, and well-coordinated contractions. This physiological efficiency is visually translated into the smooth, extensive, and symmetrical cross-shaped trajectories observed in our results.

In the OMG patients, this process is disrupted. The autoimmune attack on AChR receptors means that fewer signals get through to the muscle fibres. This leads to oculomotor weakness. The restricted range of motion seen in the OMG group trajectory graphs is a direct manifestation of this weakness. The muscles are not strong enough to move the eye to its full extent. The irregular and jerky paths reflect the underlying pathophysiology. The muscle's reduced capacity results in an inability to achieve the full range of motion observed in healthy individuals. This finding is consistent with the clinical understanding of the disease.

3.2.2. *The potential of OMG-glasses for characterizing ocular motility*

Current diagnostic methods for OMG have known limitations. Blood tests can be negative in up to half of the patients with purely ocular symptoms. Electrodiagnostic tests such as RNS may lack sensitivity in mild cases. The clinical assessment of eye movement is often subjective and dependent on the examiner's experience.

The OMG-glasses offer a novel approach for objectively characterizing ocular motility differences. The primary advantage of this method is its objectivity. The device provides numerical data, the ranges and path lengths, that are independent of subjective interpretation. This quantitative output could provide clinicians with a more objective basis for diagnosis. The device could be particularly useful in cases where other tests are inconclusive. For instance, a patient with typical symptoms but negative antibody tests could be evaluated with the OMG-glasses. A demonstrably restricted trajectory could provide strong supportive evidence for a characterization of seronegative OMG.

Furthermore, the device measures the functional impact of the disease. It directly assesses what the patient is experiencing: a limitation in their ability to move their eyes. This is a very clinically relevant measure. The simplicity and non-invasive nature of the test also make it highly suitable for repeated use. This could allow clinicians to monitor the progression of the disease over time or to objectively assess a patient's response to treatment. A measurable improvement in the trajectory graph after starting medication would be a clear indicator of therapeutic efficacy.

3.2.3. *Limitations*

It is important to acknowledge the limitations of this research. As a pilot study, the primary

goal was to establish a proof of concept. The findings, while encouraging, should be interpreted with caution.

The most significant limitation is the small sample size and absence of replicates. Single measurements were obtained from each participant without replicates, preventing assessment of test-retest reliability. Future studies should include multiple testing sessions per participant to establish measurement reproducibility. With only eight participants in each group, it was not possible to make broad generalisations. A larger study is required to confirm that these findings are statistically significant and representative of the wider population. The post-hoc power analysis indicated that with n = 8 per group, this pilot study was adequately powered (n ~ 26 per group) to detect the very large effects observed but would be underpowered to detect smaller, potentially clinically meaningful differences which may be less dependent on fatigue.

Importantly, this study did not include patients with other conditions that cause restricted eye movements, such as thyroid eye disease, cranial nerve palsies, or other forms of ophthalmoplegia. Therefore, the specificity of the observed trajectory patterns for OMG cannot be established from this data, unless, as speculated, the sensitivity of directional ratios to duration normalization differs between OMG and other ocular neurological conditions. The current findings demonstrate differentiation between healthy controls and known OMG patients, but do not establish that the device can distinguish OMG from other causes of ocular motility dysfunction. The current protocol relied on verbal instructions to maintain head position, which may not have been uniformly successful across all participants. Additionally, the use of a manual target (experimenter's finger) introduces potential variability in target speed, position, and consistency across trials. Future iterations should incorporate a chin rest or head stabilization mechanism and replace the manual target with automated on-screen fixation points to standardize the stimulus presentation.

Potential confounders were not controlled or systematically corrected for in this pilot study, including: [1] age and sex distribution between groups, which may differ and could influence baseline ocular motility; [2] refractive status of participants, as uncorrected refractive errors could affect gaze tracking accuracy; [3] medication state of OMG patients, particularly the timing of acetylcholinesterase inhibitor doses relative to testing; [4] time of day of testing, given that diurnal variability is characteristic of OMG with symptoms typically worsening throughout the day; [5] degree of eyelid occlusion from ptosis, which may have interfered with pupil detection in some patients; and [6] variability in camera-to-eye distance across participants, which could affect the pixel-to-degree conversion.

As noted in Section 3.1.4, the H:V ratio analysis found that, when normalized by session duration, the between-group differences were no longer significant, suggesting that fatigue-related effects may have confounded the results; although; as discussed above, this very confounding factor could be converted into a disease differentiator. The brief protocol duration may not adequately capture the

fatigability characteristic of OMG, while simultaneously being long enough for fatigue to differentially affect performance. An alternative interpretation (as discussed prior) would be that the combination of a significant non–duration-normalized H:V ratio with a non-significant duration-normalized H:V ratio is indicative of the observed pattern reflecting an underlying ocular motility deficit rather than fatigue acting merely as a confounding factor. Directional asymmetries emerge during task performance due to fatigable neuromuscular weakness in OMG but attenuate when scaled to exposure duration. This pattern highlights a dynamic manifestation of oculomotor impairment rather than a fixed directional bias.

The pixel-to-degree conversion was based on geometric ~ and was not validated against a gold-standard eye tracking system. While our uncertainty analysis (Section 2.4.4) demonstrated that the observed differences exceeded estimated measurement error, formal calibration would strengthen confidence in the quantitative values reported.

Another limitation is the prototype nature of the hardware. The current prototype monitors only the right eye. Since OMG symptoms often present asymmetrically, affecting one eye more than the other initially, unilateral assessment may miss early-stage disease affecting the contralateral eye or may underestimate disease severity if the more affected eye is not monitored. While the prototype is functional, the current OMG-glasses prototype could be improved in terms of ergonomics and stability. Involuntary head movements by the participants, although discouraged, could have introduced minor artifacts into the data. A more refined design with better head stabilization could improve the accuracy of the measurements.

Finally, the study did not include patients with other neurological or ophthalmological conditions that can also affect eye movement. To establish the specificity of this test for OMG, future studies would need to include control groups with other disorders. As stated in section 3.2, the sensitivity of directional ratios to duration normalization may be hypothesized to differ between neuromuscular junction disorders such as OMG and conditions characterized by more fixed mechanical or neurogenic constraints (e.g., thyroid eye disease or cranial nerve palsies), which can be tested using the OMG-glasses.

3.2.4. *Perspective*

This study lays the groundwork for a promising new area of research. A larger-scale validation study is the most critical next step. This would involve recruiting a much larger cohort of OMG patients and healthy controls. This would allow for a robust statistical analysis of the data and would help to establish clear cut-off values to distinguish between healthy and pathological eye movement.

The data analysis can also be made more sophisticated. The current analysis focused on the range of motion. Future versions of the software could incorporate the analysis of eye movement velocity, acceleration, and the quantification of saccadic intrusions. These advanced metrics may provide even greater sensitivity for detecting subtle abnormalities.

There is also potential to apply machine learning techniques. A computer algorithm could be trained on a large dataset of trajectory graphs. The goal would be to develop a model that can automatically classify a new, unseen trajectory as either "healthy" or "indicative of OMG". Such a tool could serve as a powerful and automated screening or decision-support system for clinicians.

Standardization of the experimental protocol using automated screen-based targets and physical head restraints would eliminate experimenter-related confounders and improve reproducibility. Longer duration protocols with repeated measurements could be designed to specifically assess the fatigability characteristic of OMG, which could not be evaluated with the current brief protocol. To establish specificity, future studies should include control groups with other conditions affecting ocular motility, such as thyroid eye disease and cranial nerve palsies.

Future iterations of the OMG-glasses should incorporate bilateral eye tracking with synchronized cameras monitoring both eyes simultaneously. This is essential for early detection given the characteristically asymmetric presentation of OMG, and would allow assessment of inter-ocular differences that may be diagnostically valuable.

A formal calibration procedure should be developed and validated against a gold-standard eye tracking system to ensure accurate pixel-to-degree conversion and enable comparison across different device configurations and patient populations. Longer duration protocols with repeated measurements could be designed to specifically assess the fatigability characteristic of OMG, which is difficult to capture with the current brief protocol. Such protocols could include sustained gaze tasks with measurement of performance decline over time. To establish specificity, future studies should include control groups with other conditions that affect ocular motility, such as thyroid eye disease, cranial nerve palsies, and chronic progressive external ophthalmoplegia. Future clinical validation studies will require formal IRB approval and should include systematic collection and correction for potential confounders including age, sex, medication timing, refractive status, and time of day.

This pilot study demonstrated that a wearable, camera-based device can quantify the deficits in ocular motility associated with known cases of OMG. The OMG-glasses represent a feasible and innovative approach that has the potential to become a valuable, objective tool in the characterization and management of this challenging condition.

4. Conclusion

The early and accurate characterization of OMG remains a significant clinical challenge. The fluctuating nature of the symptoms and the limitations of existing tests can lead to delays in starting appropriate management. This research was undertaken to explore a new technological approach to address this problem. We successfully designed, built, and tested a novel wearable device, termed the OMG-glasses. This device, paired with computational analysis,

provides a quantitative and objective way to assess ocular motility.

Our pilot study yielded encouraging results. We demonstrated a measurable difference in the eye movement patterns between healthy individuals and patients with OMG. The healthy control group exhibited a full and symmetrical range of motion, represented by well-defined trajectory graphs. The patient group, however, consistently showed a restricted and erratic range of motion. This was evident both visually in the trajectory graphs and numerically in the calculated metrics. These findings support our initial hypothesis. The quantitative analysis of eye movement; particularly when metrics can measure time-dependent, fatigable neuromuscular impairment - with additional selectivity being conferred by the sensitivity of those metrics to this fatigable neuromuscular impairment - may serve as a valuable sensitive as well as selective biomarker for the disease.

The primary significance of this work lies in demonstrating that quantitative eye movement analysis can differentiate between known OMG patients and healthy individuals. The OMG-glasses offer an objective, non-invasive, and low-cost method to characterize ocular motility deficits. The statistically significant differences observed ($p < 0.01$ for all motility metrics) with large effect sizes provide evidence that this approach warrants further investigation in larger studies that include other conditions affecting eye movement.

In conclusion, this research served as a successful proof of concept. It demonstrated that a wearable device can capture measurable differences in eye movement patterns between known OMG patients and healthy individuals, with all three-motility metrics showing statistically significant differences ($p < 0.01$) and large effect sizes. While this study establishes differentiation capability rather than utility for diganosis, the OMG-glasses represent a promising approach that warrants further investigation with larger sample sizes and inclusion of other conditions affecting ocular motility.

Author contributions

Padmaja Gandhi: Conceptualization, including identification of the clinical problem through literature review and understanding of OMG pathophysiology; Hardware design and assembly, including component selection (ESP32 S3, OV2640 camera, IR LEDs), circuit design, and physical fabrication of the OMG-glasses prototype; Software development of the Python-based pupil tracking and trajectory analysis program; Experimental design and protocol development; Data collection, including participant recruitment and conducting all testing sessions; Data processing and analysis, including video processing, trajectory generation, and interpretation of results; Writing of the original draft and preparation of all figures.

Sankar Balasubramanian: Supervision of the research project; Guidance on experimental design and methodology; Technical mentorship on hardware and software development; Critical review and editing of the manuscript; Verification of statistical analysis.

Acknowledgements
The authors would like to express their sincere gratitude to Ms. Aashna Saraf and CreatED for providing the platform and opportunity to conduct this research. Finally, we wish to extend our deepest appreciation to all the participants who participated in our study; their time and cooperation were invaluable to the success of this project.

Data repository
The data and code can be found at GitHub. The link is https://github.com/sankar-mechengg/OMG-glasses-pub

5. References

1. Behbehani, R. (2023). Ocular myasthenia gravis: A current overview. *Eye and Brain*, 15, 1–13. https://doi.org/10.2147/EB.S389629

2. Nair, A. G., Patil-Chhablani, P., Venkatramani, D. V., Gandhi, R. A. (2014). Ocular myasthenia gravis: A review. *Indian Journal of Ophthalmology*, 62(10), 985–991. https://doi.org/10.4103/0301-4738.145987

3. Evoli, A., Iorio, R. (2020). Controversies in ocular myasthenia gravis. *Frontiers in Neurology*, 11, Article 605902. https://doi.org/10.3389/fneur.2020.605902

4. Axelsen, K. H., Kjær Andersen, R., Andersen, L. K., Vissing, J., Witting, N. (2024). Ocular versus generalized myasthenia gravis: a continuum associated with acetylcholine receptor antibody titers. Neuromuscular Disorders, 43, 39–43. https://doi.org/10.1016/j.nmd.2024.07.002

5. de Meel, R. H. P., Raadsheer, W. F., van Zwet, E. W., Tannemaat, M. R., Verschuuren, J. J. G. M. (2019). Ocular Weakness in Myasthenia Gravis: Changes in Affected Muscles are a Distinct Clinical Feature. Journal of Neuromuscular Diseases, 6(3), 369–376. https://doi.org/10.3233/jnd-190407

6. Kim, K. H., Kim, S. W., Shin, H. Y. (2021). Initial Repetitive Nerve Stimulation Test Predicts Conversion of Ocular Myasthenia Gravis to Generalized Myasthenia Gravis. Journal of Clinical Neurology, 17(2), 265. https://doi.org/10.3988/jcn.2021.17.2.265

7. Mehnert, A., Bershan, S., Kollmus-Heege, J., Gerischer, L., Herdick, M. L., Hoffmann, S., et. al. (2024). Identifying patients at risk for myasthenic crisis with hemogram and inflammation-related laboratory parameters – a pilot study. Frontiers in Neurology, 15. https://doi.org/10.3389/fneur.2024.1297997

8. Nelke, C., Stascheit, F., Eckert, C., Pawlitzki, M., Schroeter, C. B., Huntemann, N., et. al. (2022). Independent risk factors for myasthenic crisis and disease exacerbation in a retrospective

cohort of myasthenia gravis patients. Journal of Neuroinflammation, 19(1). https://doi.org/10.1186/s12974-022-02448-4

9. Cleary, M., Williams, G. J., Metcalfe, R. A. (2008). The Pattern of Extra-Ocular Muscle Involvement in Ocular Myasthenia. Strabismus, 16(1), 11–18. https://doi.org/10.1080/15569520701830992

10. Leong, Y.-Y., Vasseneix, C., Finkelstein, M. T., Milea, D., Najjar, R. P. (2022). Artificial Intelligence Meets Neuro-Ophthalmology. Asia-Pacific Journal of Ophthalmology, 11(2), 111–125. https://doi.org/10.1097/apo.0000000000000512

11. Vinciguerra, C., Bevilacqua, L., Lupica, A., Ginanneschi, F., Piscosquito, G., Rini, N., et. al. (2023). Diagnosis and Management of Seronegative Myasthenia Gravis: Lights and Shadows. Brain Sciences, 13(9), 1286. https://doi.org/10.3390/brainsci13091286

12. Barton, J. J. S. (1998). Quantitative ocular tests for myasthenia gravis: a comparative review with detection theory analysis. Journal of the Neurological Sciences, 155(1), 104–114. https://doi.org/10.1016/s0022-510x(97)00265-7

13. Kocak, G. S., Tütüncü, M., Adatepe, N. U., Yerlikaya, B. D., Kara, E., Atas, A., Yener, M., et. al. (2021). A novel diagnostic method for myasthenia gravis. Muscle & Nerve, 64(3), 328–335. https://doi.org/10.1002/mus.27353

14. Nguyen, E. M. N. L., Clough, M. J., Fielding, J., White, O. B. (2025). A video-oculography study of fixation instability in myasthenia gravis. Frontiers in Neurology, 16. https://doi.org/10.3389/fneur.2025.1493418

15. Kee, H. J., Yang, H. K., Hwang, J.-M., Park, K. S. (2019). Evaluation and validation of sustained upgaze combined with the ice-pack test for ocular myasthenia gravis in Asians. Neuromuscular Disorders, 29(4), 296–301. https://doi.org/10.1016/j.nmd.2018.12.011

16. Chatzistefanou, K. I., Kouris, T., Iliakis, E., Piaditis, G., Tagaris, G., Katsikeris, N., et. al. (2009). The Ice Pack Test in the Differential Diagnosis of Myasthenic Diplopia. Ophthalmology, 116(11), 2236–2243. https://doi.org/10.1016/j.ophtha.2009.04.039

17. Peeler, C. E., De Lott, L. B., Nagia, L., Lemos, J., Eggenberger, E. R., Cornblath, W. T. (2015). Clinical Utility of Acetylcholine Receptor Antibody Testing in Ocular Myasthenia Gravis. JAMA Neurology, 72(10), 1170. https://doi.org/10.1001/jamaneurol.2015.1444

18. Sanders, D. B., Arimura, K., Cui, L., Ertaş, M., Farrugia, M. E., Gilchrist, J., et. al. (2019). Guidelines for single fiber EMG. Clinical Neurophysiology, 130(8), 1417–1439. https://doi.org/10.1016/j.clinph.2019.04.005

19. Giannoccaro, M. P., Paolucci, M., Zenesini, C., Di Stasi, V., Donadio, V., Avoni, P., et. al. (2020). Comparison of ice pack test and single-fiber EMG diagnostic accuracy in patients

referred for myasthenic ptosis. Neurology, 95(13). https://doi.org/10.1212/wnl.0000000000010619

20. Tomschik, M., Renaud, E., Jäger, F., Paternostro, C., Rath, J., Rinner, W., et. al. (2023). The diagnostic and prognostic utility of repetitive nerve stimulation in patients with myasthenia gravis. Scientific Reports, 13(1). https://doi.org/10.1038/s41598-023-30154-5

21. Lamb, C. J., Rubin, D. I. (2020). Sensitivity and specificity of repetitive nerve stimulation with lower cutoffs for abnormal decrement in myasthenia gravis. Muscle & Nerve, 62(3), 381–385. https://doi.org/10.1002/mus.26999

22. Kouyoumdjian, J. A., Paiva, G. P., Stålberg, E. (2020). Concentric Needle Jitter in 97 Myasthenia Gravis Patients. Frontiers in Neurology, 11. https://doi.org/10.3389/fneur.2020.600680

23. Guan, Y.-Z., Cui, L.-Y., Liu, M.-S., Niu, J.-W. (2015). Single-fiber Electromyography in the Extensor Digitorum Communis for the Predictive Prognosis of Ocular Myasthenia Gravis. Chinese Medical Journal, 128(20), 2783–2786. https://doi.org/10.4103/0366-6999.167354

24. Patil-Chhablani, P., Nair, A., Venkatramani, D., Gandhi, R. (2014). Ocular myasthenia gravis: A review. Indian Journal of Ophthalmology, 62(10), 985. https://doi.org/10.4103/0301-4738.145987

25. Zhu, L., Chen, J., Yang, H., Zhou, X., Gao, Q., Loureiro, R., et. al. (2024). Wearable Near-Eye Tracking Technologies for Health: A Review. Bioengineering, 11(7), 738. https://doi.org/10.3390/bioengineering11070738

26. Seo, H., Chung, W. G., Kwon, Y. W., Kim, S., Hong, Y.-M., Park, W., et. al. (2023). Smart Contact Lenses as Wearable Ophthalmic Devices for Disease Monitoring and Health Management. Chemical Reviews, 123(19), 11488–11558. https://doi.org/10.1021/acs.chemrev.3c00290

27. Molina-Cantero, A. J., Lebrato-Vázquez, C., Castro-García, J. A., Merino-Monge, M., Biscarri-Triviño, F., Escudero-Fombuena, J. I. (2024). A review on visible-light eye-tracking methods based on a low-cost camera. Journal of Ambient Intelligence and Humanized Computing, 15(4), 2381–2397. https://doi.org/10.1007/s12652-024-04760-8

28. Linh, V. T. N., Han, Seunghun, Koh, E., Kim, S., Jung, H. S., Koo, J. (2025). Advances in wearable electronics for monitoring human organs: Bridging external and internal health assessments. Biomaterials, 314, 122865. https://doi.org/10.1016/j.biomaterials.2024.122865

29. Sirin, T. C., Karaaslan, Z., Arkali, B. N., Bekdik, P., Akinci, T., Candan, F., et. al. (2022). Is Video-Oculography a Predictive Test for Myasthenia Gravis with Ocular Symptoms? Neurology India, 70(1), 80–86. https://doi.org/10.4103/0028-3886.336330

30. Liu, Y., Zhou, Jin. (2025). A review of Eye-Tracking Applications in biophilic design. Building and Environment, 267, 112179. https://doi.org/10.1016/j.buildenv.2024.112179

31. Narcizo, F. B., dos Santos, F. E. D., Hansen, D. W. (2021). High-Accuracy Gaze Estimation for Interpolation-Based Eye-Tracking Methods. Vision, 5(3), 41. https://doi.org/10.3390/vision5030041

32. Barsingerhorn, A. D., Boonstra, F. N., Goossens, J. (2018). Development and validation of a high-speed stereoscopic eyetracker. Behavior Research Methods, 50(6), 2480–2497. https://doi.org/10.3758/s13428-018-1026-7

33. International Electrotechnical Commission. (2006). IEC 62471: Photobiological safety of lamps and lamp systems. Geneva, Switzerland: IEC.