

Original Article

A novel fiber Bragg grating system for eye tracking

Sharath Umesh^a, Shweta Pant^a, Srivani Padma^{a,b}, Sumitash Jana^c, Varsha Vasudevan^e, Aditya Murthy^c, Sundarrajan Asokan^{a,d,*}

^a Department of Instrumentation and Applied Physics, Indian Institute of Science, Bangalore, India

^b Department of Electrical Communication Engineering, Indian Institute of Science, Bangalore, India

^c Centre for Neurosciences, Indian Institute of Science, Bangalore, India

^d Applied Photonics Initiative, Indian Institute of Science, Bangalore, India

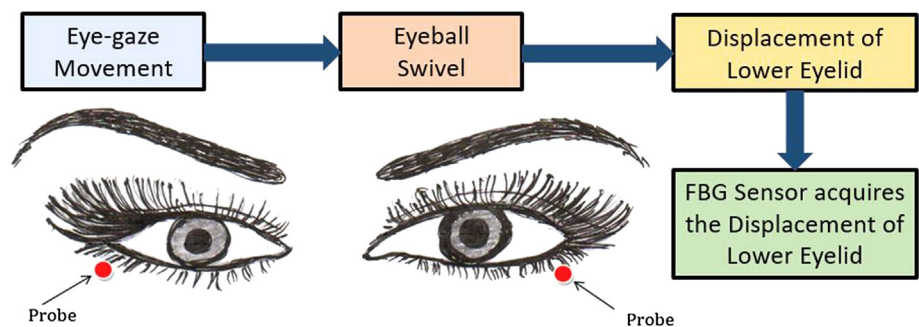
^e Centre for Biosystems Science and Engineering, Indian Institute of Science, Bangalore, India



HIGHLIGHTS

- FBGET is novel, non-invasive, and easy to mount eye tracking methodology.
- FBGET can be utilized as a point of care device.
- FBGs are electrically and chemically inert, hence suitable for biomedical sensing.
- FBGET tracks both eyes simultaneously eliminating time synchronization complexity.
- FBGET can facilitate diagnosis of ophthalmological/neurological disorders.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:

Received 29 August 2018

Revised 19 December 2018

Accepted 20 December 2018

Available online 31 December 2018

Keywords:

Fiber Bragg grating sensor

Eye tracker

Eye muscular movement detection

ABSTRACT

Eye movement evaluation is vital for diagnosis of various ophthalmological and neurological disorders. The present study proposes a novel, noninvasive, wearable device to acquire the eye movement based on a Fiber Bragg Grating (FBG) Sensor. The proposed Fiber Bragg Grating Eye Tracker (FBGET) can capture the displacement of the eyeball during its movements in the form of strain variations on a cantilever. The muscular displacement generated by the eyeball over the lower eyelid, by its swiveling action while moving the gaze on a target object, is converted into strain variations on a cantilever. The developed FBGET is investigated for dynamic tracking of the eye-gaze movement for various actions of the eye such as fixations, saccades and main sequence. This approach was validated by recording the eye movement using the developed FBGET as well as conventional camera-based eye tracker methodology simultaneously. The experimental results demonstrate the feasibility and the real-time applicability of the proposed FBGET as an eye tracking device. In conclusion, the present study illustrates a novel methodology involving displacement of lower eyelid for eye tracking application along with the employment of FBG sensors to carry out the same. The proposed FBGET can be utilized in both clinical and hospital environment for diagnostic purposes owing to its advantages of wear-ability and ease of implementation making it a point of care device.

© 2019 The Authors. Published by Elsevier B.V. on behalf of Cairo University. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

Introduction

The eye movement is routinely investigated for the assessment of ocular motor functioning and is widely used to study covert

Peer review under responsibility of Cairo University.

* Corresponding author.

E-mail address: sasokan@iisc.ac.in (S. Asokan).

<https://doi.org/10.1016/j.jare.2018.12.007>

2090-1232/© 2019 The Authors. Published by Elsevier B.V. on behalf of Cairo University.

This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

cognitive processes in normal and pathological conditions. Though there are different types of eye movements such as saccades, smooth pursuit, vergence and vestibulo-ocular movements, research is largely focused on saccades. Saccades are rapid eye movements which focus the target image on the fovea central, a region at the centre of the retina possessing highest visual acuity. Since the seminal work of Yarbus [1], which showed that saccades are not random eye movements but are planned and are changed when the cognitive context changes; many covert processes like attention, decision making, planning of movements have been studied using saccades. Tracking of saccadic movements are used for detection of the onset and evolution of many psychological and cognitive disorders. For example, saccades are known to be perturbed in numerous neuro-developmental and neuropsychiatric disorders, such as Parkinson's disease [2,3], Alzheimer's disease [4], Autism [5], Schizophrenia [6] and Attention-Deficit-Hyperactivity Disorder [7]. Therefore, saccadic eye movements are used as a simple and non-invasive clinical diagnostic tool for studying the above-mentioned disorders.

Previously, clinicians used to rely upon direct observation of subjects' eye movements. However, the recent advancement in various detection/measurement methodologies has facilitated clinicians to acquire precise quantitative eye movement characteristics. Further development of easy and cost-effective ways to detect eye movements would tremendously help in the early diagnosis of many disorders. Eye movement trackers are mainly divided based on the sensing methodology employed, as contact type or non-contact type. The contact type eye movement trackers include electrodes mounted around the eye or head mount devices, whereas non-contact type eye movement trackers use cameras to track the movement of the pupil. Traditionally, eye movement acquisition at very high spatial and temporal rates has been carried out using scleral search coil [8,9] and dual-Purkinje image tracker [10]. Some of the modern eye movement detection techniques include electro-oculography, limbal tracking, video-oculography and the magnetic search coil [11]. However, search coils are invasive and hence not comfortable method for eye tracking and could cause changes to the dynamics of the eye movement itself [12]. Though the dual-Purkinje image tracker [10] avoids the problem posed by the search coil method, its utilization is limited by factors such as its expense and range limitations [13]. Additionally, even though the camera-based systems are easy to use, one of the major limitations of this methodology is the requirement of the eyes to be wide open; thus, these methods perform poorly when the subject looks down, which makes the eye aperture smaller. Further, camera-based methods cannot be used to track the eye movements during Rapid Eye Movement sleep. With this background, the present study proposes a novel, non-invasive, wearable type eye movement sensing methodology using a Fiber Bragg Grating (FBG) sensor. The developed Fiber Bragg Grating Eye Tracker (FBGET) has the ability for real time acquisition of the displacement of the lower eyelid caused due to swiveling of the eyeball while making a particular eye movement. The FBGET is a contact type eye movement tracker in which a probe rests on the lower eyelid. The FBGET essentially converts the muscular displacement of the eye into strain variations on a cantilever which is acquired by the FBG sensor bonded over it. The FBGET is a standalone system comprising of features such as electrical passiveness (no electric power required at the sensor end), highly sensitive, chemically inert, wear-ability, compactness, light-weight and portable which make FBGET as one of the best point-of-care diagnostic devices [14]. Also, the use of FBG sensors brings out other advantages such as insensitivity to electromagnetic interference, low fatigue and fast response, which makes the proposed FBGET an effective eye movement tracker [15–18].

Material and methods

Fiber Bragg grating

FBG is basically periodic modulation of the refractive index of the core of a single-mode photosensitive optical fiber, along its axis [14]. The periodic modulation in refractive index is brought by exposing the optical fiber to a spatial interference pattern created by an KrF excimer laser. The characteristic feature of an FBG is to reflect a narrow band of wavelength which satisfies the Bragg condition, when broadband light is launched into the fiber consisting FBG [15]. The centre wavelength of the reflected band is termed as Bragg wavelength (λ_B) of the FBG and it is governed by Eq. (1).

$$\lambda_B = 2n_{\text{eff}}\Lambda \quad (1)$$

Here, Λ is the periodicity or inter-distance of the grating and n_{eff} is the effective refractive index of the fiber core. In the present work, FBG sensors of gauge length of 3 mm are fabricated in a photo sensitive germania doped silica fiber using the phase mask inscription method [16], whose Bragg wavelength is around 1531 nm.

Any external perturbation such as strain, temperature, etc., at the grating site of the FBG sensor alters the periodicity of the grating as well as the effective refractive index of the fiber, which in turn shifts the reflected Bragg wavelength. Hence, by interrogating the shift in Bragg wavelength, the parametric external perturbation can be effectively quantified [17,18]. For example, the strain effect on an FBG sensor is expressed as

$$\Delta\lambda_B = \lambda_B \left[1 - \frac{n_{\text{eff}}^2}{2} [P_{12} - \nu(P_{11} + P_{12})] \right] \varepsilon \quad (2)$$

where P_{11} and P_{12} are the components of the strain-optic tensor, ν is the Poisson's ratio and ε is the axial strain change [19]. The strain sensitivity of FBG inscribed in a germania-doped silica fiber is found to be approximately 1.20 pm/ $\mu\varepsilon$ [20]. Furthermore, FBGs are also sensitive to temperature changes, however the temperature effect on the FBG sensor in the present study can be neglected, as the experiment is conducted in a controlled environment and the experimental duration is small.

Fiber Bragg Grating Eye Tracker (FBGET)

A stainless-steel cantilever of dimension 30 mm in length, 3 mm in width and 0.1 mm in thickness is attached perpendicularly to a copper plate. The copper plate is in turn attached to a rubber sheet. The other end of the stainless-steel cantilever is attached to a plastic probe. The rubber sheet facilitates the mounting of the device on the cheek of the subject while the plastic probe rests on the lower eyelid of the subject. FBG sensor is bonded on the stainless steel cantilever to acquire the strain variations over it. Collectively, these components constitute to form the FBGET as shown in Fig. 1(a). The appropriate positioning of the FBGET probe is significant to acquire the eyeball movement efficiently.

The FBGETs are attached to the cheeks of the subject in such a way that the probe resides on the lower eyelid as depicted in Fig. 1(b). The eye gaze movement is initiated by the six muscles which surrounds the eyeball effectively making it angular movement (angle subtended at the eye by its gaze) due to spherical geometry of the eyeball. The eyeball swivels in the socket with each eye movement making the bottom eyelid move along with it. Consequentially, the probe resting on the bottom eyelid also moves thereby creating a strain variation over the stainless-steel cantilever. Therefore, the angular movement due to the eye gaze movement is the measurand parameter and its subsequent

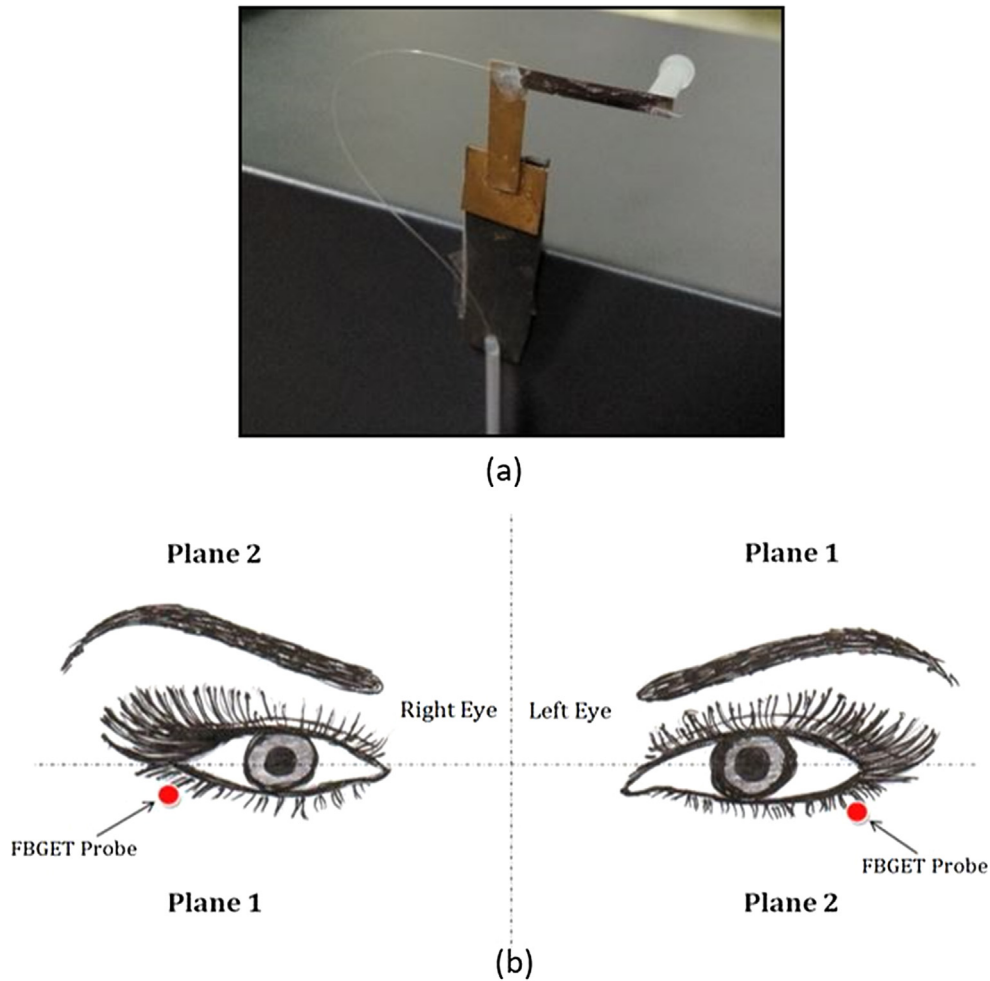


Fig. 1. (a) Pictorial representation of FBGET, (b) Positional placement of the FBGET probe on the lower eyelid along with the plane consideration.

displacement on lower eye lid produces a strain on the cantilever of the FBGET. These strain variations are acquired by the FBG sensor bonded over the cantilever. Effectively, the recorded signal is an indicator of the eye gaze movement with respect to saccade amplitude. Thus, the FBGET converts the displacement of the eyeball during its movement into strain variations over the cantilever.

In the present study, the whole eye gazing space is divided into two planes as be observed in Fig. 1(b). Plane 1 and plane 2 are defined in detail in the “Eye Movement Pattern” section. It is observed that the FBGET probe on the right eye captures the gaze movement in plane 1, with better sensitivity. Similarly, the FBGET probe on the left eye captures the gaze movement in plane 2, with better sensitivity. This variation in sensitivity arises due to the selected position of the FBGET probe on the lower eyelid. The recorded data from the FBG sensor can be further processed to identify the basic characteristic movements of the eye such as saccades, fixations and blinks.

The strain sensitivity of the developed FBGET is evaluated by calibration trials against a motorized translational stage. The probe of the FBGET is brought in contact with a shaft as shown in Fig. 2(a) and this shaft is connected to a motorized translational stage. Subsequently, a uniformly increasing displacement is imparted on the probe of the FBGET via shaft, using the motorized motion controller. The corresponding variations in FBGET Bragg wavelength is acquired using FBG interrogator and is compared with the displacement imparted by the shaft the FBGET probe. The shift in Bragg wavelength is observed to be in good agreement with the displacement imparted on the probe as observed by the correlation

coefficient of 0.99 obtained by the responses of both the right and left FBGET as shown in as can be seen in Fig. 2(b). Further, the strain sensitivity of the FBGET is evaluated by the slope of the response curve and in the present study, the strain sensitivity is found to be $0.12 \text{ nm}/^\circ$ ($120 \text{ pm}/^\circ$) and $0.09 \text{ nm}/^\circ$ ($90 \text{ pm}/^\circ$) on left and right FBGET, respectively. The variation in the strain sensitivity of the FBGET on the left and right eye may be attributed to the positional variation of the FBG sensor on the cantilever.

ISCAN eye tracker

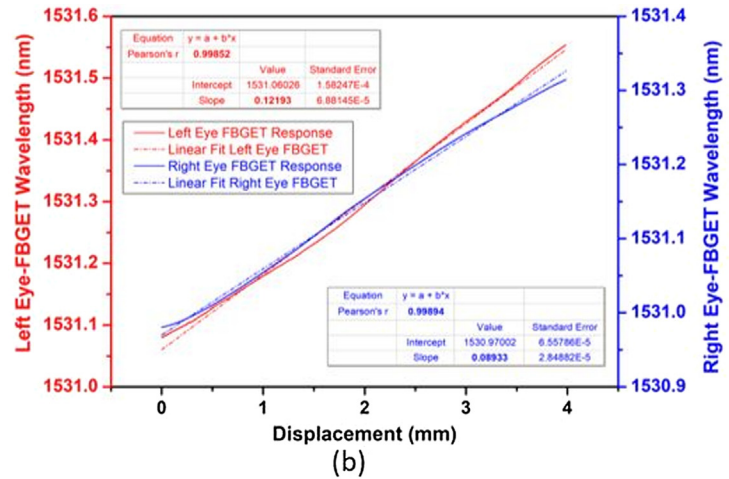
To validate the proposed FBGET, the obtained results are compared with an infrared based pupil tracker (ISCAN ETL 200, Boston, MA, USA), which has the ability to track the pupil of the eye with a precision of $\sim 0.5^\circ$. The ISCAN is mounted on the desk in front of the subject in order to monitor the eye movements at a frequency of 240 Hz and a spatial accuracy of $\sim 1^\circ$ of visual angle as shown in Fig. 3. The stimuli are generated in software called TEMPO/Video-SYNC (Reflective Computing, St. Louis, MO, USA) which also receives the data in real time. The eyeball movement patterns performed by the subject are recorded simultaneously through ISCAN and FBGET and then compared against each other to validate the developed sensor methodology.

Eye movement pattern

During investigations, the screen is placed at a distance of 57 cm from the subject’s eye such that a 1 cm shift on the screen



(a)



(b)

Fig. 2. (a) FBGET Calibration test setup, (b) Response of left and right FBGET during calibration.

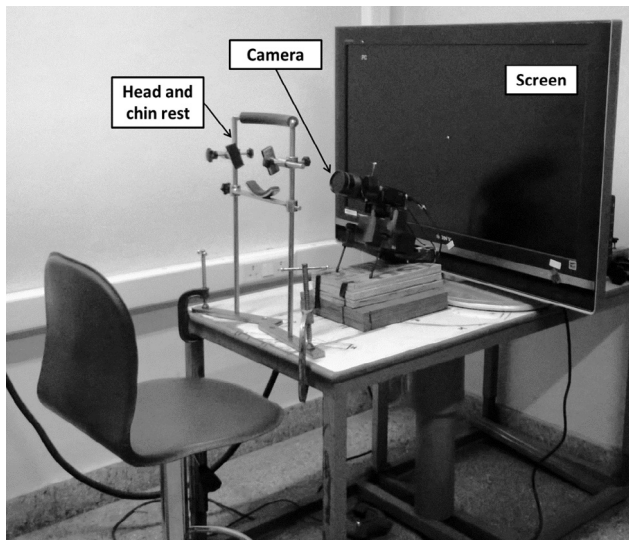


Fig. 3. Experimental setup of the ISCAN eye tracker with display unit.

subtends roughly 1° of visual angle at the eye. The subject's head is locked in place with the aid of a head and chin rest, in order to ensure that there should be no lateral movement of the head. The head and chin rest ensure that the head is locked in order to prevent the relative movement of head during the performance of the eye movement. Prior to the experiment, calibration for the ISCAN is carried out and the eye gains are adjusted in TEMPO. Each trial begins with the fixation of the subject's gaze at the center of the screen on a white fixation square. After a delay of 500 ± 50 ms, a target (green square) is displayed at the periphery to which the subject makes a saccade, after which the subject's gaze returns to the center of the screen on the white fixation square.

The peripheral targets are displayed at an eccentricity of 5° , 9° and 13° from the center. The possible locations of target at the three eccentricities in the two planes which are displayed during the experiment are shown in Fig. 4(a). Here, the pattern is displayed such that the 5° , 9° and 13° angular movement of the eye is initiated from the fixated center. The two planes considered are perpendicular to each other as shown in Fig. 4(a), wherein up-gaze or adduction and down-gaze or abduction with respect to the right eye will be referred to as plane 1, while up-gaze or

adduction and down-gaze or abduction with respect to the left eye will be referred to as plane 2. The sequence of steps in the experimental paradigm employed in the present study is shown in Fig. 4(b).

Experimental methodology

The present study has been approved by the Institutional Human Ethics Committee (IHEC), Indian Institute of Science. The experiments carried out in the present study are within the guidelines of the IHEC for human studies that approved the protocol. Also, the subjects were given a detailed explanation about the experimental procedure and their written consent was obtained prior to the experiments. Totally, 6 subjects in the age group of 24–30 years (3 males and 3 females) volunteered for the present study.

The FBGETs were attached on the cheeks of the subject on either side, such that the probe of the FBGET was positioned on the lower eyelid as shown in Fig. 5. The subjects were requested to fix their gaze at the centre white square, followed by an eye movement sequence along plane 1 and plane 2. The data from both the FBGETs were recorded simultaneously through SM 130–700 FBG Micron Optics Interrogator, which can acquire the data with a sampling rate of 1 kHz and with a resolution of 1 pm shift in Bragg wavelength which effectively converts to $0.81 \mu\epsilon$ strain variation. Simultaneously, the gaze movement during the same procedure was acquired using ISCAN methodology which was utilized for validating the developed FBGET.

Results

The obtained results have been divided into sections for better understanding. Three different sections namely *Plane 1*, *Plane 2* and *Main Sequence* describes the obtained results during various trials performed by the subject. Section *Plane 1* and *Plane 2* includes the results obtained while the subject follows the eye pattern for plane 1 and plane 2 respectively whereas section *Main Sequence* includes all the results obtained by analysis carried out to study the main sequence.

Plane 1

The FBGET response obtained from the right eye (raw data acquired in the form of peak reflected Bragg Wavelength) while following the pattern along plane 1, is shown in Fig. 6. Further,

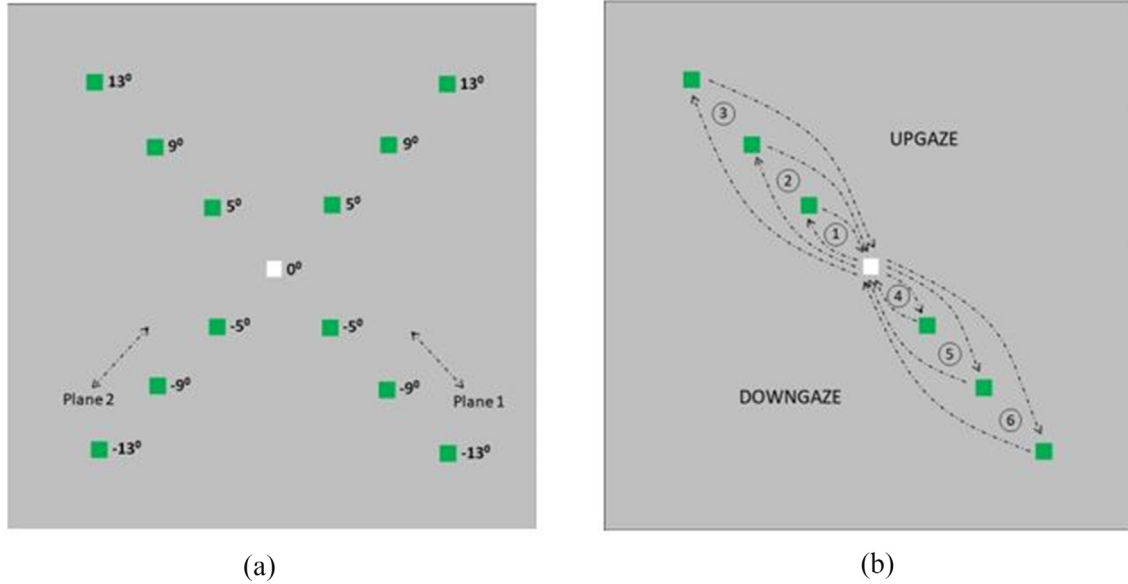


Fig. 4. (a) Target at all three eccentricities in plane 1 and plane 2, (b) Sequence of steps in the experimental paradigm.



Fig. 5. Experimental Setup with FBGET mounted on the subject and ISCAN placed on a nearby reference plane.

Fig. 7(a) and (b) quantifies the response (in shift in reflected Bragg wavelength) obtained from the right eye FBGET for the same individual subject whose data is shown in Fig. 6. The reflected Bragg

wavelength (strain variation = $1.22 \times$ shift in wavelength) obtained for each saccadic movement from 0° to 5°, 9°, 13° for 10 different trials performed by the said subject with the left and right eye is shown in Fig. 7(a) and (b), respectively. The slope obtained from this data was utilized as the scaling factor to convert the wavelength shift obtained from the FBG sensor into an angular movement of the eye.

A typical trial is considered for illustration, which consisted of movements to three eccentricities along two planes and the saccadic eye movement was recorded simultaneously by ISCAN and FBGET. The results obtained simultaneously from the ISCAN and FBGET for 10 individual trials performed by the same subject are depicted in Fig. 7(c). The error bars at every angular movement shows the standard deviation obtained with respect to ten trials performed by the subject. Further, the mean amplitude of the angular movement obtained from FBGET was compared with the corresponding mean amplitude of the angular movement obtained from the ISCAN, as shown in Fig. 7(d) and both methodologies are found to be in good agreement with each other with a correlation coefficient of 0.99.

Plane 2

The data obtained from FBGET for the eye movement along plane 2 was analyzed using the same procedure as plane 1.

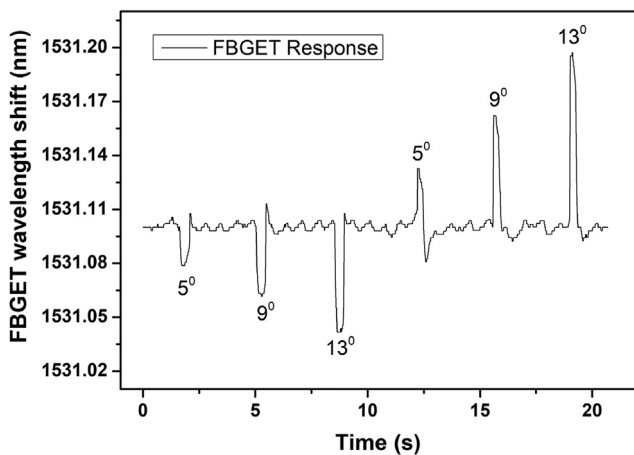


Fig. 6. The FBGET response from right eye for movement along plane 1 (eye movement pattern as shown in Fig. 4) which includes three eccentricities on either side of centre fixation.

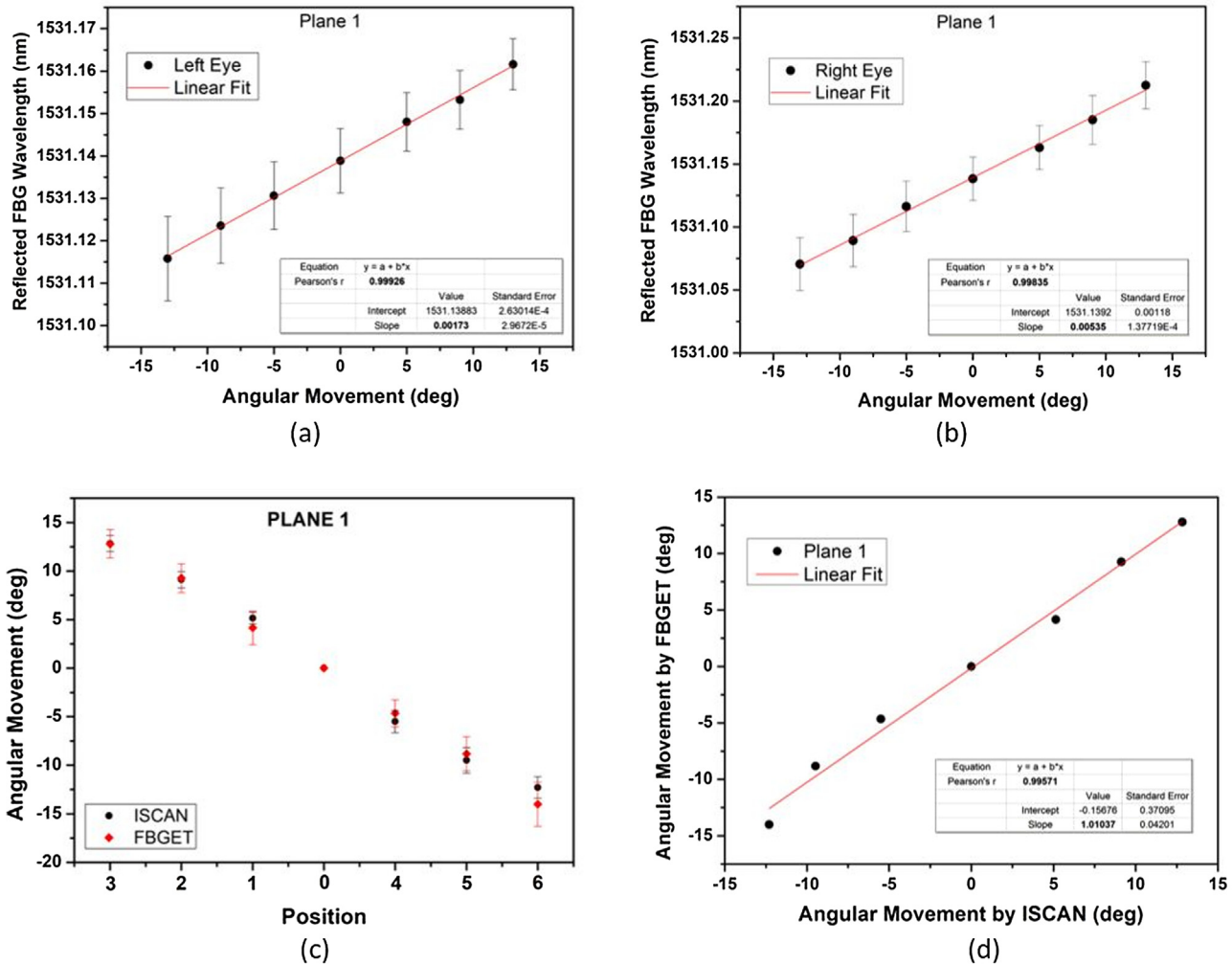


Fig. 7. Individual response of FBGET for eye movements along plane 1 with (a) left eye and (b) right eye for 10 trials repeatedly performed by the same subject. (c) Angular movement acquired from right eye for movement along plane 1 from ISCAN and FBGET for 10 trials performed by single subject, (d) Comparison of angular movement obtained from ISCAN and FBGET along plane 1 for right eye.

Furthermore, a near linear response with a Pearson's r of 0.99 (correlation coefficient obtained through regression analysis) for left and right eye was observed between the response of FBGET and the angular movement from both eyes as shown in Fig. 8(a) and (b). Also, the angular movement obtained from both the methodologies simultaneously for all the 10 trials, performed by the same subject, were in good accordance with each other, as shown in Fig. 8(c). The comparison of results obtained from FBGET and ISCAN for the particular subject is shown in Fig. 8(d).

Main sequence

The kinematic profile of saccades is highly stereotypical where the saccade peak velocity and duration show a monotonic relationship with saccade amplitude [21]. This relationship is called the main sequence. In the present study, the responses from ISCAN and FBGET recorded simultaneously were analyzed to evaluate the main sequence responses. The eye movement velocity obtained for each of these saccades from FBGET and ISCAN are shown in Fig. 9(a) and (b), respectively. The main sequence graph of time duration with respect to amplitude obtained by FBGET for 5 selected trials carried out by the subject are shown in Fig. 10(a). Further, Fig. 10(b) shows the main sequence graph of time duration with respect to amplitude obtained from ISCAN during the same

trials. Further, the other aspect of main sequence, which is the peak velocity comparison with respect to amplitude was carried out for the same 5 trials performed by the subject which is shown in Fig. 10(c) and (d).

To further validate the efficacy of the FBGET to acquire the angular motion from off-center positions, trials which begin with a fixation offset of 5° was carried out. The results of the same is shown in Fig. 11.

Discussion

Plane 1

As explained in the earlier section, plane 1 consists of eye movement of up-gaze or adduction and down-gaze or abduction with respect to the right eye. Also, for such eye movements the strain variations obtained from the right eye is dominant than the strain variation obtained from the left eye during the trial due to the chosen position of the FBGET probe. It can be observed from Fig. 6, that in addition to changes in wavelength shift, there is also polarity reversal in the response of the FBGET when the subject is performing the downgaze or abduction when compared to the up gaze or adduction. This polarity reversal is due to the compressive strain experienced by the FBG sensor during up gaze and the tensile

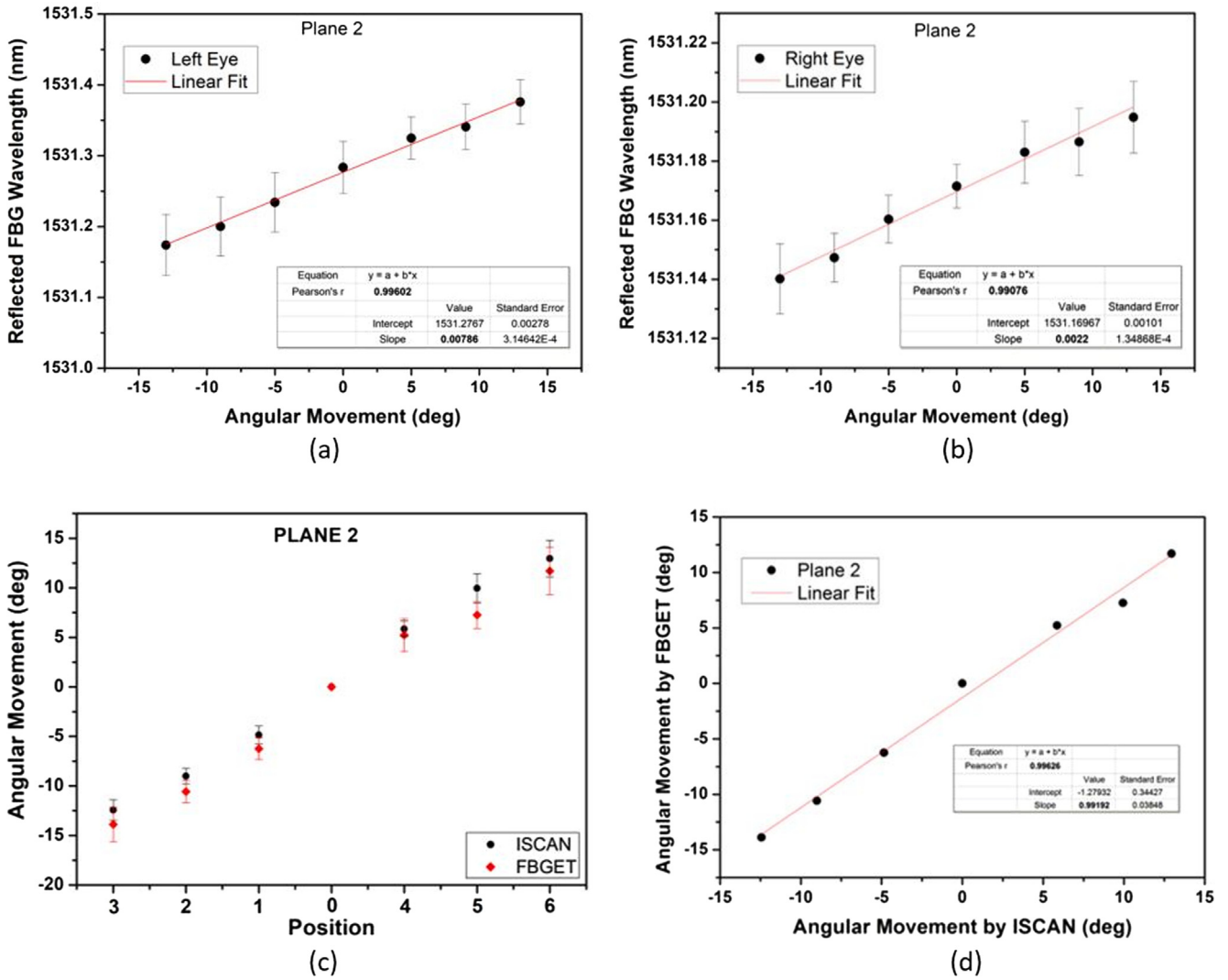


Fig. 8. Individual response of FBGET for eye movement along plane 2 with (a) left eye and (b) right eye performed by the same subject repeatedly for 10 trials. (c) Angular movement acquired from left eye for movement along plane 2 from ISCAN and FBGET for 10 trials performed by single subject, (d) Comparison of angular movement obtained from ISCAN and FBGET simultaneously for plane 2 for left eye.

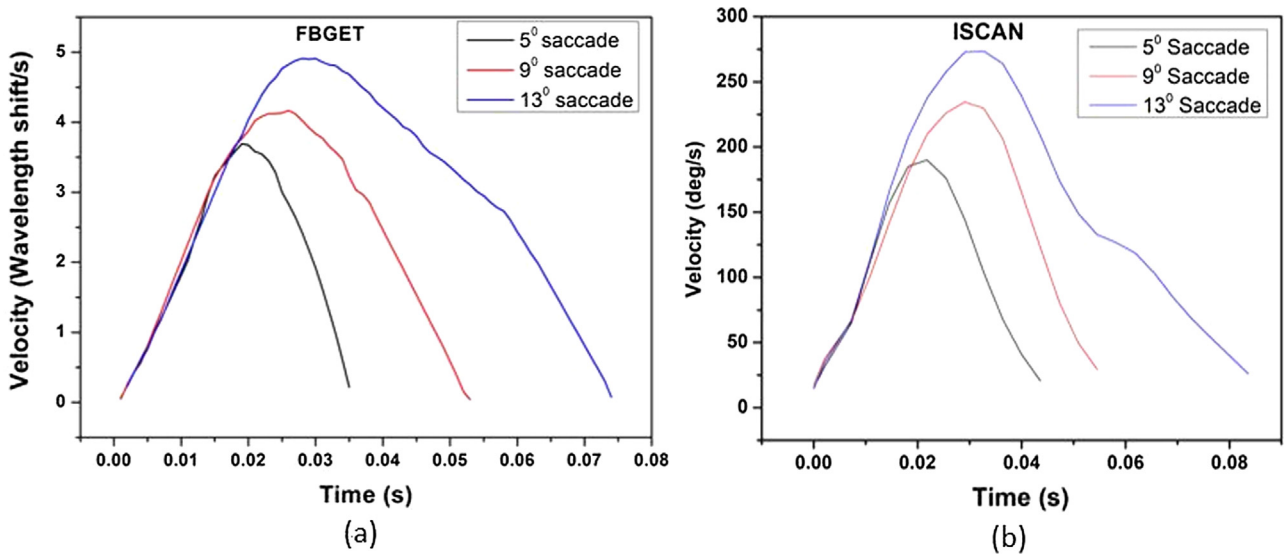


Fig. 9. Velocity of eye movement for varying saccades acquired simultaneously from (a) FBGET and (b) ISCAN.

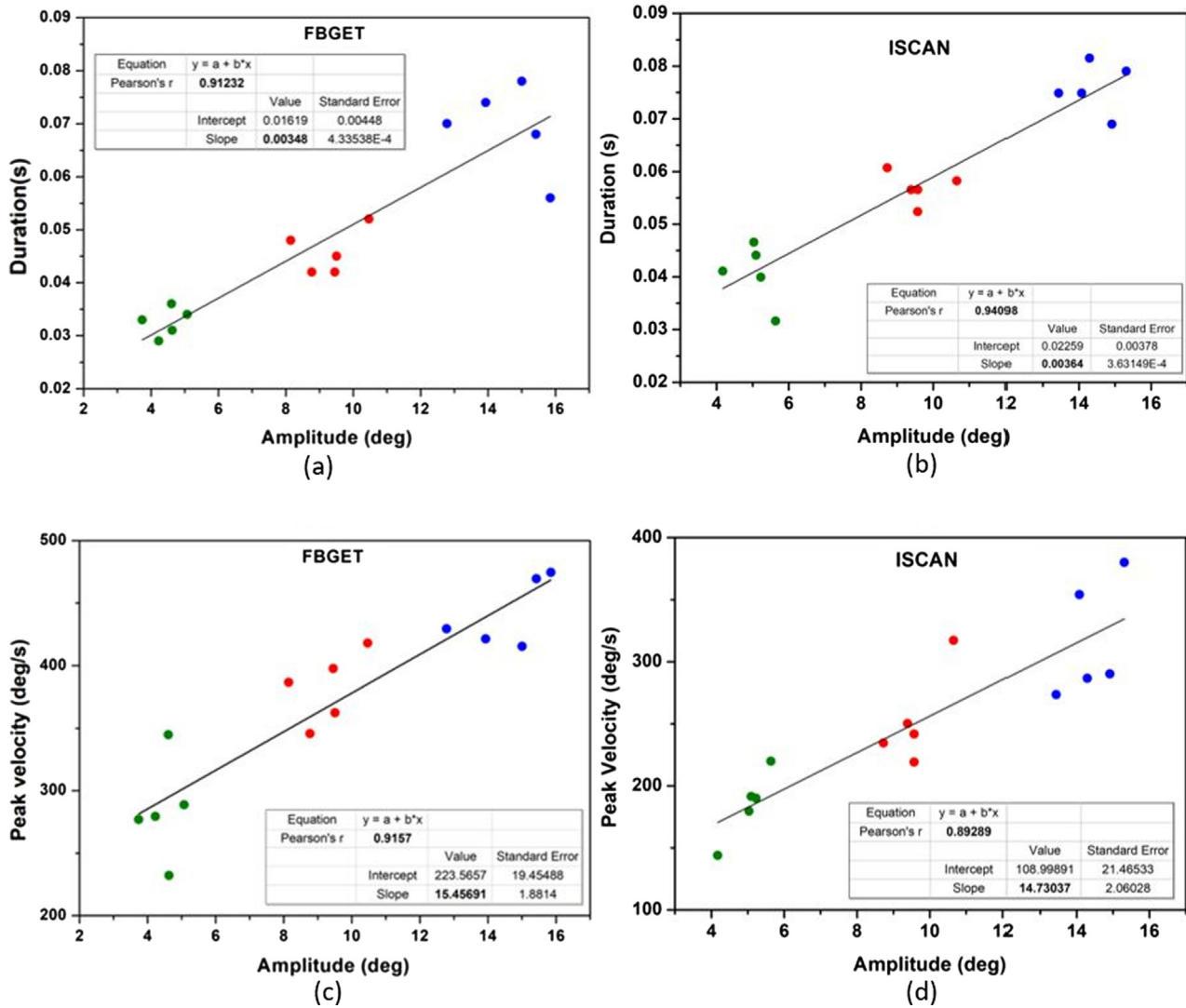


Fig. 10. The time duration recorded for varying saccades acquired from (a) FBGET and (b) ISCAN for repeated trials performed by a subject, and the peak velocity recorded for varying saccades acquired from (c) FBGET and (d) ISCAN for repeated trials performed by a subject.

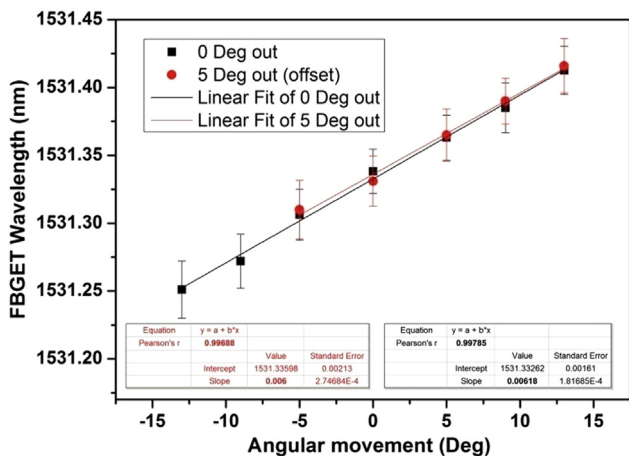


Fig. 11. FBG Wavelength obtained from FBGET starting from 0° and 5° positions.

strain experienced by the FBG sensor during downgaze. A high correlation coefficient of 0.99 (Fig. 7) was obtained between the amplitude of eye movement at the target and the resultant shift

in wavelength experienced by FBGET. The FBGET's wavelength shift exhibits a linear response for both the eyes.

The angular movement of eye obtained from both ISCAN and FBGET methodology were found to be in good agreement with each other. Since the ISCAN camera tracked the movement of one eye only, the validation was carried out for the right eye movement only. Moreover, the angular movement obtained from the ISCAN as well as the FBGET, are in good agreement shown by the obtained correlation coefficient of 0.99 for the said subject.

Plane 2

On similar lines of the analysis carried out on plane 1, a similar analysis was performed with the eye movement pattern along Plane 2, which consisted of eye movements of up-gaze or adduction and down-gaze or abduction with respect to the left eye. Such eye movements, at this chosen position of the FBGET probe, is dominated by the left eye due to the selected position of the probe in the lower eyelid. The comparison of results obtained from FBGET and ISCAN for the particular subject in plane 2 also were in good agreement with a correlation coefficient of 0.99 as shown in Fig. 8(d), validating the efficacy of the FBGET as an eye tracker.

Main sequence analysis

In addition to the stereotypical bell-shaped saccade velocity profile (Fig. 9), the FBGET data also closely matched the velocity profile observed in ISCAN. The small variations in the velocity profiles may be attributed to the different sensing principles along with the variation in the data sampling rate of ISCAN with 250 Hz and FBG Interrogator with 1 kHz. Further, the relation obtained between time duration and amplitude seems to be linear. It is observed from Fig. 10(a) and (b), that the trends in both the responses were similar (obtained slope of 3.4 ms/° for FBGET and 3.6 ms/° for ISCAN) with a small variation in time duration which may again be attributed to the difference in the sampling rate of acquisition between FBGET and ISCAN. Furthermore, the peak velocity and the amplitude were compared against each other to observe the relationship between the two as shown in Fig. 10(c) and (d). The slopes obtained by both methods were in good accordance with each other, i.e. a slope of 15.45/s with FBGET and slope of 14.73/s with ISCAN is recorded. FBGET and ISCAN responses have been found to be in good agreement with each other. These comparisons prove that the main sequence of FBGET is in good agreement with the main sequence of ISCAN, which again proves the efficiency of the FBGET as an eye tracker when compared to ISCAN.

For further validation, two sets of trials were analyzed to validate the FBGET for the offset trials, in which the first sequence of eye movement began from a 0° position (black curve) and the second sequence of the eye movement starts from a 5° position (red curve). The slopes of both the sequence were nearly same (6.0 pm/° for red curve and 6.1 pm/° for black curve) with the high correlation coefficient of 0.99 for both the sequence. It is interesting to note that there is good concurrence between the two curves obtained from FBGET, as shown in Fig. 11. This proves that the change in the pattern does not affect the ability of the FBGET as an eye tracker.

To summarize, the eye movement tracking trials carried out with the FBGET and ISCAN showed a good agreement between them, with respect to the angular movement in two planes, the main sequence and offset trials. Multiple trials were carried out to observe the repeatability of the device and methodology. The main sequence obtained from both FBGET and ISCAN methodologies were found to be in good agreement. Consequentially, anomalies in the eye movement may be observed by main sequence obtained from FBGET, which may be an indicator of neuro-developmental and neuro-psychiatric disorders. In the present study, the effect on FBG sensor due to temperature variations are neglected because the duration of experimental trial is short, and the experiments are conducted in a temperature-controlled environment. Moreover, it is imperative to understand that the temperature changes from the starting to ending of an individual eye pattern trial (temperature change within 20 s) only will affect the recorded measurements. The change in temperature in the temperature-controlled room within a trial duration of 20 s is found to be <0.02 °C and therefore, the effect of temperature on the obtained readings during this study are deemed to be negligible. Nevertheless, when the FBGET is employed for trials of longer durations, then an auxiliary FBG sensor bonded on the separate stainless-steel plate will be employed for temperature compensation. This auxiliary FBG sensor on stainless steel plate will respond to explicit temperature changes. The temperature response of this auxiliary FBG will comprise of both the FBG sensitivity towards temperature (10 pm/°C) along with the thermal expansion of the stainless steel due to temperature variations (thermal expansion coefficient of 16 μm/m °C). Therefore, the data from this auxiliary FBG sensor can be used to negate the complete temperature effect

on the FBGET (FBG temperature sensitivity and thermal expansion of material).

One of the major limitations of the FBGET is the possibility of errors arising due to positional offsets during the mounting of the FBGET on the subject's eyelid. The amplitude of measured signal of the FBGET is varying with respect to the positioning of the probe on the lower eyelid. Due to these positional offsets, a calibration trial involving a reference pattern needs to be performed before starting the eye movement tracking. In addition, due to the selected positions of the FBGET probe on eyelid, the response of FBGET is dominating in one plane than the other plane. An individual FBGET employed on one eye provides the 1-D information of eye gaze movement and therefore it is essential to consider data from both the eyes for complete eye tracking applications to make FBGET an efficient 2-D eye tracker. However, the developed FBGET is a non-invasive, easy to wear, non-tedious, optical method of eye tracking which can be employed on the bedside of a patient. Therefore, the developed FBGET can prove to be an efficient methodology to acquire the eyeball movement.

Conclusions

A novel, non-invasive, wearable Fiber Bragg Grating Eye Movement Tracker (FBGET), has been developed, to acquire the angular movements of the eye. Eye gaze movement in the form of displacement variations on the eye ball are captured by the strain variation on a cantilever via a FBG sensor. Various trials have been carried out in order to compare the responses between FBGET and the widely used ISCAN eye tracker and the results obtained are found to be in good agreement, which proves the efficacy of the developed FBGET as an Eye Tracker. The elimination of time synchronization complexity employing multiple FBG sensors is facilitated in FBGET, which proves to be one of the major advantages for the simultaneous eyeball movement monitoring on both the eyes. In addition, advantages such as easy implementation and convenience of the subject as well as the medical fraternity, non-invasiveness, chemical and electrical inertness etc. make the FBGET as one of the best eye tracker which can aid as a diagnostic tool for various types of ophthalmological and neurological disorders. Further, the inherent advantages of optical fiber sensor such as small footprint, light weight, high sensitivity, no electromagnetic interference and crosstalk etc makes the FBGET suitable for efficient and convenient eyeball tracking. The present work focusses on proving the efficacy of the FBGET to acquire the eye ball movement pattern effectively along with the displacement of the lower eyelid as an indicator of the eye gaze movement. Further, the present study is extended to assess the relationships between the basic characteristic movements like saccades, fixations, smooth pursuit and blinks employing FBGET. Furthermore, the specifications of FBGET like precision, accuracy, resolution and measurement errors are presently being characterized with a substantial sample size. In addition, the authors also intend to collaborate with doctors/clinicians to test the applicability of FBGET for the diagnosis of various ophthalmological and neurological disorders.

Conflict of interest

The authors declare no conflict of interest.

References

- [1] Yarbus. In: Eye movements and vision. US: Springer; 1967. doi: <https://doi.org/10.1007/978-1-4899-5379-7>.
- [2] Owen BW, Jean AS, James AS. Ocular motor deficits in parkinson's disease. *Brain* 1983;106(3):555–70.

- [3] Ausaf AF, Neha B, Shrikanth K, Madhuri B, Vinay G, Aditya M. Impaired conflict monitoring in Parkinson's disease patients during an oculomotor redirect task. *Exp Brain Res* 2011;208(1):1–10.
- [4] Fletcher WA, Sharpe JA. Saccadic eye movement dysfunction in Alzheimer's disease. *Ann Neurol* 1986;20(4):464–71.
- [5] Pelphrey KA, Morris JP, McCarthy G. Neural basis of eye gaze processing deficits in autism. *Brain* 2005;128(5):1038–48.
- [6] Fukushima J, Fukushima K, Chiba T, Tanaka S, Yamashita I, Kato M. Disturbances of voluntary control of saccadic eye movements in schizophrenic patients. *Biol Psychiatry* 1988;23(7):670–7.
- [7] Sweeney JA, Takarae Y, Macmillan C, Luna B, Minshew NJ. Eye movements in neurodevelopmental disorders. *Curr Opin Neurol* 2004;17(17):37–4237.
- [8] Collewijn H, van der Mark F, Jansen TC. Precise recording of human eye movements. *Vision Res* 1975;15(3):447–50.
- [9] Robinson DA. A method of measuring eye movement using a scleral search coil in a magnetic field. *IEEE Trans Biomed Eng* 1963 Oct;10:137–45.
- [10] Crane HD, Steele CM. Generation-V dual-Purkinje-image eye tracker. *Appl Opt* 1985;24:527–37.
- [11] Harold EB, Scott BS. Eye movement testing in clinical examination. *Vision Res* 2013;90:32–7.
- [12] Frens MA, Van der Geest JN. Scleral search coils influence saccade dynamics. *J Neurophysiol* 2002;88(2):692–8.
- [13] Young LR, Sheena D. Survey of eye movement recording methods. *Behav Res Meth Instru* 1975;7(5):397–429.
- [14] Morey WW, Meltz G, Glenn WH. Fiber Bragg grating sensors. *Proc SPIE Fiber Optic Laser Sens VII* 1989;1169:98–107.
- [15] Othonos A. Fiber Bragg gratings. *Rev Sci Instrum* 1997;68(12):4309–41.
- [16] Hill KO, Malo B, Bilodeau F, Johnson DC, Albert J. Bragg gratings fabricated in monomode photosensitive optical fiber by UV exposure thorough a phase-mask. *Appl Phys Lett* 1993;62(10):1035–7.
- [17] Kersey AD, Davis MA, Patrick HJ, LeBlanc M, Koo KP, Askins CG, et al. Fiber grating sensors. *J Lightwave Technol* 1997;15:1442–62.
- [18] Othonos A, Kalli K. *Fiber Bragg gratings fundamentals and applications in telecommunications and sensing*. Boston: Artech House; 1999.
- [19] Tahir BA, Ali J, Rahman RA. Fabrication of fiber grating by phase mask and its sensing application. *J Optoelec Adv Mat* 2006;8(4):1604–9.
- [20] Melle SM, Alavie AT, Karr S, Coroy T, Liu K, Measures RM. A Bragg grating-tuned fibre laser strain sensor system. *IEEE Photon Technol Lett* 1993;5:263–6.
- [21] Bahill AT, Michael RC, Lawrence S. The main sequence, a tool for studying human eye movements. *Math Biosci* 1975;24:191–204.