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INFRARED- BASED BLINK DETECTING GLASSES FOR FACIAL PACING: TOWARDS A BIONIC BLINK

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Abstract

IMPORTANCE—Facial paralysis remains one of the most challenging conditions to effectively manage, often causing life-altering deficits in both function and appearance. Facial rehabilitation via pacing and robotic technology has great yet unmet potential. A critical first step towards reanimating symmetrical facial movement in cases of unilateral paralysis is the detection of healthy movement to use as a trigger for stimulated movement.

OBJECTIVE—To test a blink detection system that can be attached to standard eyeglasses and used as part of a closed-loop facial pacing system.

DESIGN—Standard safety glasses were equipped with an infrared (IR) emitter/detector pair oriented horizontally across the palpebral fissure, creating a monitored IR beam that became interrupted when the eyelids closed.

SETTING—Tertiary care Facial Nerve Center.

PARTICIPANTS—24 healthy volunteers.

MAIN OUTCOME MEASURE—Video-quantified blinking was compared with both IR sensor signal magnitude and rate of change in healthy participants with their gaze in repose, while they shifted gaze from central to far peripheral positions, and during the production of particular facial expressions.

RESULTS—Blink detection based on signal magnitude achieved 100% sensitivity in forward gaze, but generated false-detections on downward gaze. Calculations of peak rate of signal change

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(first derivative) typically distinguished blinks from gaze-related lid movements. During forward gaze, 87% of detected blink events were true positives, 11% were false positives, and 2% false negatives. Of the 11% false positives, 6% were associated with partial eyelid closures. During gaze changes, false blink detection occurred 6.3% of the time during lateral eye movements, 10.4% during upward movements, 46.5% during downward movements, and 5.6% for movements from an upward or downward gaze back to the primary gaze. Facial expressions disrupted sensor output if they caused substantial squinting or shifted the glasses.

CONCLUSION AND RELEVANCE—Our blink detection system provides a reliable, non-invasive indication of eyelid closure using an invisible light beam passing in front of the eye. Future versions will aim to mitigate detection errors by using multiple IR emitter/detector pairs mounted on the glasses, and alternative frame designs may reduce shifting of the sensors relative to the eye during facial movements.

INTRODUCTION

Facial paralysis affects up to 0.3% of the population every year in Western Europe and the United States.¹ People usually experience unilateral facial paralysis, with preserved contralateral facial movement. One of the most bothersome issues is loss of eye blink due to paralysis of the orbicularis oculi muscle on the affected side. The perpetually open eye is at risk for exposure to debris and drying, and results in chronic irritation and pain. Additionally, the loss of eye blink may lead to permanent corneal damage from ulceration or infection. Aside from the functional impairment in blinking and other facial movements, facial paralysis is also a major psychological barrier to a healthy social life, and low thresholds for observer detection of blink asymmetry have been demonstrated.^{2,3} One possible way to restore blink is through a closed-loop neural prosthesis (facial pacing device) that detects normal blinking on one side of the face, and simultaneously stimulates blinking on the paralyzed side. Since blinking is typically symmetrical, the healthy eye blink may serve as an appropriate trigger for prosthetically-assisted blink on the contralateral side in facial paralysis.

One of the challenges in using healthy blinking as a trigger for induced blinking in facial palsy is to rapidly and accurately detect healthy blinks in a non-invasive and non-disruptive manner. The most frequently proposed method for non-invasively detecting blink on the intact side is through skin surface electromyographic (EMG) recording of the orbicularis oculi muscle^{4–7}, followed by detection of periocular tissue movements through gyroscopes⁸ or accelerometers.⁹ Although these approaches demonstrate promise for accurately detecting blinks, they require placement of sensors on the face surface, which complicates device use and potentially influences dynamics of healthy blinks.

We have developed a novel approach to eye blink detection utilizing infrared (IR) emission/detection as a safe, non-contact, invisible, and inexpensive indicator of eyelid closure over the eye. Our prototype system employs an IR light-emitting diode (LED) and an IR detector mounted on a pair of glasses. The LED and detector components are positioned at the nasal and temporal aspects of one eye, causing the infrared beam to pass horizontally across the central portion of the palpebral fissure, just anterior to the corneal surface (i.e. the pupil

location when looking straight ahead). The beam remains unbroken when the eye is open, but is interrupted by the eyelashes and/or lid tissue when the upper lid descends, causing the circuit receiving the IR detector signal to register a blink.

The aim of this study was to test our IR eye blink detection apparatus in healthy participants while they assumed multiple gaze positions (i.e., primary, lateral, upwards and downwards) and facial expressions (broad smile, squinting, and eyebrow raising). By comparing video-recorded blinks versus the output of our blink detection system, we sought to establish the sensitivity of the new system to complete and partial blinks during common gaze positions and facial expressions.

METHODS

Blink Detection Prototype Glasses and Circuit

The blink detection system employs IR LEDs and detectors mounted on three pairs of laboratory safety eyeglasses as a proof of concept, with each pair of glasses differing slightly in terms of the relative position of the IR emitter/detector units in relation to the nose bridge in order to accommodate a range of adult face shapes. The three pairs had beam positions that differed by less than 2 mm in relation to the lower rim and front surface of the glasses lens. The main difference among the glasses was that pair 2 had slightly narrower nose pad separation compared to the wider nose pads of pairs 1 and 3. Additionally, pair 3 had the beam falling slightly closer to the lens surface (1.3 mm closer than pair 1, and 1 mm closer than pair 2).

For each prototype pair of glasses, the infrared LED (QEC 123; Fairchild Semiconductor Corporation) has a peak emission wavelength of 880 μm , which is also the frequency of maximal sensitivity for the matching phototransistor (QSC 114; Fairchild Semiconductor Corporation). The LED and detector components are positioned at the nasal and temporal aspects of one eye (respectively), causing the infrared beam to pass horizontally across the central portion of the palpebral fissure, just anterior to the corneal surface (Figure 1). The beam remains unbroken when the eye is open, but is interrupted by the eyelashes and/or lid tissue when the upper lid descends, causing the circuit receiving the IR detector signal to drop in output voltage (Figure 2). The LED is powered with electrical pulses at a frequency of 5.2 kHz, and the detector compares the light received during pulses versus IR light detected between pulses as a means of rejecting signal artifact due to changes in ambient light levels. An opaque light shield is mounted on the detector to reduce the potential impact of IR light entering from glancing angles (Figure 1). The IR detection circuit functions well in typical indoor and outdoor lighting conditions, except when the phototransistor directly faces the sun, or bright incandescent bulbs that are in close proximity (i.e. within a few feet).

IR light emitted from the LED in each prototype pair of glasses does not pose a known risk to the eye (e.g. lens, cornea, retina). Maximal power output of the IR LEDs was 0.62 mW as measured at the LED lens surface using an IR sensitive light meter (Ophir Nova II Meter and Photodiode Power Sensor PD300, with appropriate filter setting). Even if the LED used in our system were inadvertently directed into the eye from the corneal surface for 8 consecutive hours, the amount of light energy delivered would be 2.13 log units below the

maximal permissible exposure levels set forth by the American National Standards Institute (ANSI) code Z136 for laser safety standards (i.e. more than two orders of magnitude below a safe exposure level).

Blink Detection Participants

Twenty-four volunteers age 22–62 (10 males, 14 females; 20 Caucasians, 4 Asians, 1 African American) were recruited from the Massachusetts Eye and Ear Infirmary (MEEI) community (e.g. students, employees and visitors). Individuals with a history of eye/retinal disease, neuromuscular disease (myasthenia gravis, essential blepharospasm, facial palsy), or pathological exophthalmos (i.e.: Basedow-Graves disease) were excluded from participation. Seventeen individuals were under age 40, 6 were between 40 and 59 years old, and only 1 was over 60 years old (Table 1).

Blink Detection Apparatus and Data Collection Procedures

Blink detection system testing took place in a distraction-free room within the MEEI Facial Plastic Surgery Unit. Participants were briefly tested/screened with the three prototype pairs of eyeglasses to determine which pair provided the best blink detection given their particular orbital anatomy. They were then asked to stand 50 cm from a Smart Board Screen (SBX880) with their chin resting on an adjustable platform which stabilized their head and oriented their forward gaze directly toward the screen. The testing session began with a 101 seconds instructional video projected in the center of the screen directly in front of the participant (Figure 3). The video was a close-up view of woman's face as she explained details of the testing session, including 1) the total session length (6 minutes), 2) the need to keep the head steady and to move eyes only when instructed (rather than moving the head), 3) the task of visually tracking a large dot in various locations on the screen, and 4) the task of mimicking various facial expressions being modeled on the screen. Data collection began at the start of the introductory video in order to sample spontaneous blinking during forward gaze.

Data acquisition continued in the second part of the testing session, where participants were instructed to focus their gaze on a large dot appearing at various locations on the projection screen, without moving their head when changing their gaze position (Figure 4). The dot changed position every 5 seconds, with an audible tone indicating when the dot was changing position. The sequence of dot locations was repeated twice, and included the following sequence: Center, Center Up, Center Down, Center, Left, Left Up, Left Down, Center, Right, Right Up, Right Down, Center. This enabled testing of the effect of gaze direction on the blink detection circuit output, since upper eyelid position can potentially change based upon gaze change and position (particularly for downward gaze).

In the third part of the testing session, participants were shown photographs of four different facial expressions (neutral, smiling, squinting and eyebrows raising) and asked to mimic each expression throughout the 4 seconds each expression was shown. The neutral expression was mimicked first, and also fell between each of the other three expressions. Each time the demonstration expression changed, an audible narration accompanied the visual cue, informing participants of the desired facial expression.

Recorded data included video and audio obtained by a video camera (Canon VIXIA HF R200; 1440 × 1080 pixels, 11,951 kbps video; 48 kHz, 256 kbps audio) positioned on a tripod with a close-up frontolateral view of each participant's eye being monitored, and an output voltage from the blink detection circuit and room microphone digitized at 20 kHz using analogue-to-digital hardware (DigiData 1440 and a Cyberamp 380 programmable filter/amplifier; Molecular Devices, Sunnyvale, CA) and software (Clampex 10.2, Molecular Devices). Video files were viewed on a computer using software (Corel VideoStudio Pro X5) that allowed the viewer to indicate each point in time (frame) when a blink or eye twitch began (29.97 fps). A blink was noted when the upper and lower edge of the pupil was at least partially covered by the eyelids, and a twitch was noted when there was a conspicuous movement of one or both lids without covering the upper and lower edge of the pupil. Each video was viewed a minimum of 2 times to ensure that all blinks were noted, and observers were blinded to the blink detection circuit output. The time locations for observed eyelid movements, gaze position changes, and mimicked facial expressions were compared with absolute value and rate of change of the blink detection circuit output.

Rate of signal change, represented by the signal's derivative (i.e. instantaneous velocity), was calculated in Matlab software using the "diff" function (MathWorks Inc., Natick, MA) after down sampling from 20 kHz to 1 kHz. Signals that started from 3V and had derivative values of either -0.1 or -0.2 were scored as blinks. Of these two levels, the particular derivative threshold applied for blink assessment was determined on an individual basis according to which level produced the least amount of detection error (i.e. fewest false positives and false negatives). Once a threshold level was selected for an individual, that level was applied for blink detection throughout their recording session. Signal changes that occurred less rapidly than the applied threshold or that occurred from a staring level < 3 V were not scored as blinks, nor were signals that occurred within 250 ms of a detected blink (to avoid potential artifact associated with eye opening at the end of each blink).

To qualitatively relate blink detection circuit output (V) with change in palpebral fissure during blinking, the blink detection system was also employed for two participants (a male age 43 and female age 32) in conjunction with high-speed video recording of eyelid movement (1000 frames/sec, 240 × 256 pixels; KayPentax B/W System, Montvale, NJ).

RESULTS

At least one of the three prototype pairs of eyeglasses fit each participant adequately for blink detection. The three different glasses versions (pairs 1–3) were worn by 50%, 37.5% and 12.5% of the participants (respectively), with fairly even numbers of males and females wearing the two most commonly worn versions (pairs 1 and 2). Pairs 1 and 2 differed primarily in the position of the nose bridge pads, causing pair 1 to rest slightly lower on the face than pair 2 due to differing gaps between nose bridge pads. Pair 3 had a beam falling 1.3 mm or 1 mm further from the eye surface than pairs 1 and 2 (respectively), which provided the best blink detection during the initial testing/fitting in only 3 participants. In all four participants of Asian descent and two of the Caucasian participants, the lower rim of the glasses rested on the upper cheek (lower orbit and malar fat pad) rather than the bridge of the nose, and therefore moved with changes in facial expression, potentially decreasing

blink detection accuracy. At no time did participants report seeing light or feeling heat from the IR LED, consistent with the 880 μm peak wavelength and relatively low power output of the LED and driving circuit.

The airing of the instructional video provided an opportunity to measure spontaneous blinks from participants during a forward gaze. The 24 participants produced a range of 1–76 complete blinks (mean = 27.3, standard deviation = 17.7) during the 101 seconds of instructional video 1–76 blinks

A relatively unbroken light path between the IR emitter and detector caused a relatively high voltage output (typically 4–5 V) from the blink detection circuit. When the IR light path was broken, the circuit output voltage dropped towards a low state (typically 0–1 V; Video 1). Drops in the circuit voltage caused by eyelid obstruction of the IR light path during blinking were generally faster than when light path obstruction occurred during gaze changes and facial expressions (i.e. squinting and broadly smiling), prompting us to consider not only the direction and magnitude of signal change, but also the rate of signal change when identifying blinks from the detection circuit output (Figure 5; Video 2).

Blink detection based on change in signal magnitude achieved 100% sensitivity in forward gaze, but typically generated false detections on downward gaze and, to a lesser degree, other gaze changes as well. Blink detection based on peak rate of signal change (first derivative) during the instructional video where participants maintained a primary (forward) gaze yielded an average correct detection of 87%, with 11% false positives, and 2% false negatives (see Figure 6). Of the 11% false positives, slightly over half (6%) were associated with eye twitches (i.e. partial eyelid closures). Therefore, the system had reasonably good sensitivity for blink detection during primary gaze (missing only 2% of observed blinks on average, and missing no blinks in 14/24 participants), but falsely detected blinks when no visible eyelid movement occurred for 5% of the detected blink events. For the 21 gaze changes (starting from a primary gaze) tested in each participant, the resulting blink detection signal pattern was falsely identified as a blink 6.3% of the time for lateral eye movements, 10.4% of the time for upward movements, 46.5% of the time for downward movements, and 5.6% of the time for movements from an upward or downward gaze back to the central (primary) gaze.

Blink detection was not attempted during the mimicked facial expressions, but change in the signal baseline during these expressions would have often precluded blink detection due to interruption of the IR light beam by the upper and/or lower eyelid. Interruption in the IR light path during these expressions was typically associated with partial eyelid closure (i.e. during squinting or broad smile), but was also affected by shifting of the glasses by movement of skin at the bridge of the nose or upper cheek (i.e. during eyebrow raising and broad smile). Specifically, the IR circuit output was reduced to 2.5 V (half) or less during broad smile in 57% of participants, during squinting in 96% in of participants, and during eyebrow raising in 22% of participants.

Comparison between the blink detection circuit output and high-speed-video (1000 fps) recordings of eyelid movement indicated that the initiation of signal change (deflection)

from baseline was synchronous with visible eyelid movement (Videos 3 and 4 show circuit output voltage during eye blink and twitch, respectively). Average latency from the start of signal deflection during a blink to peak derivative was 45.6 ms (± 18.9 ms).

DISCUSSION

People typically experience facial paralysis on only one side of their face, with preserved contralateral facial movement. Since spontaneous mimetic movements are usually symmetrical, in cases of unilateral paralysis a device can record and process a biosignal when the healthy hemiface spontaneously moves. This approach to facial reanimation is referred to as closed-loop facial pacing.

With regard to the eye blink, the signal recorded from the healthy eye can be processed to trigger a train of electrical pulses that initiate an artificial blink from the paralyzed eye. We are developing a closed-loop facial pacing device to restore eye blink in individuals with unilateral paralytic lagophthalmos. Individuals affected by acute reversible facial paralysis with a prognosis for recovery within 12 months would benefit from an external apparatus to facilitate eye closure during waking hours, until the recovery process is complete. Individuals affected by irreversible facial paralysis would more likely benefit from a permanent, implanted neuroprosthesis¹⁰ utilizing intramuscular stimulation, which could also be driven by biosignals from the healthy eye.

Our envisioned closed-loop eye blink pacing system for acute facial palsy is an assembly of three different components, aimed at: 1) detecting blink events on the healthy side, 2) processing the blink-related biosignal to activate a stimulation unit, and 3) pacing the contralateral facial nerve or orbicularis oculi muscle, thus eliciting a biomimetic eye blink. Both detection and stimulation hardware could ultimately be incorporated into the frame of glasses, but we expect that intermediate iterations will be tethered between the glasses and a small rechargeable signal processing unit worn under the clothes.

Herein, we describe a novel approach to eye blink detection that provides a robust and reliable indication of eyelid closure, while maintaining the advantages of IR emission/detection as a safe, non-contact, invisible, and inexpensive reporter of blink occurrence and duration. Our laboratory developed a blink detection system employing an IR light emitting LED and a phototransistor (IR detector) mounted on laboratory safety eyeglasses as a proof of concept, but could be configured to clip onto nearly any pair of glasses. We mounted IR emitter/detector components in slightly different locations on three pairs of glasses in order to improve eyelid movement sensing across participants, with pairs 1 and 2 differing primarily on the vertical height of the IR beam in relation to the eye surface, and pair 3 differing in the beam's horizontal position. These slight variations helped us accommodate for differences in subject facial anatomy, however clinically deployed versions of the glasses would need to provide adjustable positioning of the IR emitter/detector pair in relation to the frame (and therefore in relation to the user's orbit) to accommodate a wider range of face shapes and achieve optimal blink detection.

Eye blink detection using IR light or miniature cameras is commonly performed in the context of gaze tracking (for visual scanning research, eye-controlled systems, etc.), but requires bulky, conspicuous hardware that would be impractical for detecting/restoring blink throughout the day. These systems demonstrate the safe utilization of IR light for detecting eye and eyelid position, particularly considering that they typically shine IR light directly into the eye¹¹, whereas our proposed system directs the IR light in front of the eye surface.

Infrared light has also long been used to measure blinks in animal research by detecting the change in light reflectance from the eye surface versus the upper and/or lower eyelid surface during lid closure.^{12–14} The globe of the eye is relatively translucent to IR light, causing little detected reflectance when an IR emitter and detector pair is positioned directly in front of the eye. In laboratory animals with fur-covered eyelids (e.g., rats and rabbits), IR reflectance increases substantially when the lids close over the eye surface due to the high IR reflectivity of fur. Human eyelids are much less reflective to IR light, generating more subtle differentiation between open versus closed eyelids. Nevertheless, IR reflectance has been used to detect blink behavior in humans as an indicator of drowsiness in automotive drivers¹⁵ and aviators.¹⁶ Sleep Diagnostics Pty Ltd (Melbourne, Australia) has developed such a method and a device (called Optalert®) specifically for use while driving. This system provides a measure of the amplitude-velocity ratio for blinks and saccades¹⁷, but it is unclear how rapidly the hardware is able to detect the onset of blink movement since a rapid response latency is not required for drowsiness assessment.

Successful application of IR-based blink detection for facial pacing requires minimal detection errors, since both false triggers and missed blinks result in unilateral eye closure that can be conspicuous and bothersome. A challenge of the envisioned blink detection application is identifying the best trade-off between type I and II errors; in other words, between making the paralyzed eye spuriously wink versus missing true blink events, respectively. Our results demonstrated that blink detection based on signal magnitude achieved 100% sensitivity in forward gaze, but generated false detections whenever participants looked downward due to the natural lowering of the upper lid (breaking the IR beam). Thresholding on peak rate of signal change (first derivative) helped distinguishing blinks from slower, gaze-related lid movements, correctly rejecting 54% of downward gazes as non-blinks. Analysis of blink detection during forward gaze revealed that 5% of the detected blink events did not correspond to any visible eyelid movement (type I error), and that only 2% of observed blinks went undetected (type II error). The application of error minimization algorithms on an individual basis could reduce this error by optimizing detection thresholds, or at least strike a better balance between error types.

Blink detection with the initial proof-of-concept configuration of a single IR LED (emitter) and phototransistor (detector) could be improved by adding one or more additional emitters and/or detectors. This would decrease the likelihood of non-blink lid movement (associated with change in gaze position) from generating false-positive blink events. Having a row of 2 or 3 opposing emitter/detector pairs mounted parallel to the eye surface may provide an alternative pathway for the IR beams to travel when the lids move up or down in concert, yet remain separated (e.g. during downward gaze). Moreover, an array of emitter/detectors may

make the detection system more robust to shifting of eyeglass position as people move their heads or move the skin on the bridge of their nose during facial expression.

A special requirement of the envisioned device is detecting blinks events early enough to trigger and pace synchronous movements. Human visual information updates at rates of approximately 30–33 Hz¹⁸, allowing for 33 ms in right/left movement asymmetry before being noticed. However, eyelid closure during blink is not instantaneous, since the process of eyelid closing and reopening spans approximately 100–300 ms¹⁹, so dys-synchrony of one eye in relation to the other will produce an asymmetry in lid position lasting much of the blink duration plus the latency between the faster and slower sides. The longer the blink latency between the two eyes, the longer the asymmetry period and greater the discrepancy in right/left palpebral fissure size throughout the blink. In the present report, average latency from the start of blink movement to blink detection (i.e. peak of IR signal derivative) was 45.6 ms (± 18.9 ms), indicating that stimulated blink would be conspicuously asymmetrical if triggered from our current detection system.

Our research group recently quantified the perceptual impact of side-to-side blink movement asymmetry using video files that systematically altered to differ in the latency of right versus left blink initiation (0–264 ms latency difference across 6 tested steps). Results showed that over 65% of participants detected asymmetrical eye blinks at the shortest tested delay (1 video frame or 33 ms³). In addition, side-to-side asymmetry in blinking was perceived as unnatural sooner than other tested facial expressions (i.e. smile, raising eyebrows, and lower lip depression), demonstrating observers' particular sensitivity to blink asymmetry compared to other facial movements. Further work is required to reduce detection latency in the proposed system, perhaps through detection threshold optimization and individualized sensor alignment, since asymmetrical eyelid movement and static position can easily draw unwanted attention.^{2,3}

Electromyography (EMG) has long been used as a neural interface for prosthetic control^{20,21} and represents the most popular recording technology applied to closed-loop facial pacing^{4–7}, holding potential for real-time eye blink detection and pacing. Indeed, EMG recording can detect the onset of the electrical activity of the orbicularis oculi muscle 11 ms before the lid movement starts for voluntary and spontaneous blinks.¹⁹ The downside of skin surface EMG-based eye blink detection is its vulnerability to electrical crosstalk with adjacent muscles; addressing this noise requires the application of software filters and implies approximately 20% missed blink events.⁹ Blink detection approaches that are IR-based, EMG-based, and perhaps a combination of the two are likely to be fruitful towards development of an external blink restoration system. Moving forward, blink elicitation studies in unilateral facial palsy patients are necessary to complete the link between blink detection and generation in our envisioned biomimetic prosthesis.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Figure 1. Frontal (A) and lateral (B) views of a prototype blink detection pair of glasses with an arrow demonstrating the path in infrared (IR) light traveling horizontally across the corneal surface from the IR LED (nasal side) towards the IR detector (temporal side).

Figure 2.

Flow diagram of the eye blink detection system, showing: 1) infrared emitter and detector units in relation to the eye, 2) variable gain of the preamplifier receiving the phototransistor output, 3) signal filtering, and 4) final output of the circuit as a time-varying analog voltage ranging from 0–5 V. An unbroken beam generates a 5 V output whereas a completely obstructed beam generates a 0 V output, with partial obstruction producing voltages in between these extremes.

Figure 3.

A participant is shown standing in position for the 6 minute blink detection recording session, photographed during the initial 102 second instructional video. An adjustable chin rest help participants maintain a forward head position, and a forward gaze was held through the instructional video (during which spontaneous blinks were detected).

Figure 4. Photograph of a participant assuming an upper right gaze position as she looked at a target (blue dot). Targets appeared in the four corners of the Smart Board screen, in addition to center, upper center, and lower center (see text for presentation sequence).

Figure 5.

Examples of the blink detection circuit output for a blink (left column) and downward gaze (right column). The detector receives a relatively unobstructed beam during forward gaze, producing an output in the 4–5 V range (upper row, time zero), but drops in voltage when the beam is broken by the lowering upper lid during a blink or looking downward. This drop in voltage is typically more rapid for blinking than gaze-related lid movement, as shown by the slope (downward pointing arrows) and by the 1st derivative of the output signals (lower

row). The difference in peak derivative for blink versus downward gaze is highlighted by the dotted lines and double-headed arrow.

Figure 6.

Average blink detection performance during primary (forward) gaze. 6% of the false positives were associated with slight eyelid movement or twitches (without lids covering the pupil) noted by naive observers reviewing session video recordings, whereas 5% of false positives had no observable lid movements. 2% of blinks observed in the video recordings did not reach the blink detection threshold, and therefore went undetected (false negatives).

Table 1

Study Population. Participants were classified based on sex, race and age range.

Study Population	Age (yo)	Caucasian	Asian	African American	Total
Males	<40	7	2	0	9
	40-59	1	0	0	1
	>60	0	0	0	0
Females	<40	7	1	0	8
	40-59	3	1	1	5
	>60	1	0	0	1
Total		19	4	1	24