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Computer-Aided Methodology for Syndromic Strabismus Diagnosis

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Abstract Strabismus is a pathology that affects approximately 4 % of the population, causing aesthetic problems reversible at any age and irreversible sensory alterations that modify the vision mechanism. The Hirschberg test is one type of examination for detecting this pathology. Computer-aided detection/diagnosis is being used with relative success to aid health professionals. Nevertheless, the routine use of high-tech devices for aiding ophthalmological diagnosis and therapy is not a reality within the subspecialty of strabismus. Thus, this work presents a methodology to aid in diagnosis of syndromic strabismus through digital imaging. Two hundred images belonging to 40 patients previously diagnosed by an specialist were tested. The method was demonstrated to be 88 % accurate in esotropias identification (ET), 100 % for exotropias (XT), 80.33 % for hypertropias (HT), and 83.33 % for hypotropias (HoT). The overall average error was 5.6Δ and 3.83Δ for horizontal and vertical deviations, respectively, against the measures presented by the specialist.

Keywords Medical images · Strabismus · Syndromic diagnosis · Hirschberg test · Images processing · Pattern recognition · Support vector machines

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Introduction

Strabismus is a type of eye anomaly in which they lose parallelism to each other. While one eye gazes at a frontal point in space, the other deviates towards one side, or even upwards or downwards. The result is that the brain receives two images with different focuses, instead of two images that merge into a single unique one. There are several types of strabismus: the affected eye can deviate towards the nose (convergent strabismus), to the sides (divergent strabismus), or upwards or downwards (vertical strabismus). It also can occur with a combination of horizontal and vertical deviation, for example towards the nose and upwards.

To diagnose strabismus, tests of visual acuity, eye bottom examination or fundoscopy, external verification of the eye (including the cornea, sclera, conjunctiva, iris, and lens), and motility examination with the Cover test and Hirschberg test are performed. The Hirschberg test consists of a small beam of light focused into the patient's eyes to determine if the reflection in each eye is located in the same place in the cornea.

The everyday use of high-technology resources for aiding in ophthalmologic diagnosis and therapy is not yet a reality within the strabismus sub-specialty. The difficulty in finding experienced physicians in this sub-area outside large urban centers makes such technologies essential, as its lack greatly hampers the precocious diagnosis of strabismus in locations far from these centers. However, some tools have been or are being developed to allow medical professionals to make reliable decisions concerning visual pathologies.

Jolson et al. [14] developed a device called a trophorometer to measure the position and the ocular motion using computer image processing, to aid in the diagnosis of phorias and tropias. Buquet and Charlier [2] studied the application of the photo-oculographic technique to the quantification of static orientations of the eye that are determined from the relative positions of corneal reflex and pupil images.

Fisher et al. [9] developed an expert system using an artificial neural network for the differential diagnosis[1] of manifest vertical-deviation strabismus. The magnitude of the deviation manually input by the specialist to the neural network was measured using the alternate prism cover test. The diagnostic accuracy was 100 % for a clinical data set of 65 PCT examinations.

The present research is concerned with the study and development of an easy, fast, and low-cost way of automatically evaluating the likelihood of a patient having strabismus and directing the diagnosis thereof. We seek to develop a method that can be accessible to generalists or to ophthalmologists not trained in strabismus diagnosis. Our goal is to use a digital camera and a computer with software implemented according to the methodology proposed in this work.

Almeida et al. [1] presented a computational method for the automatic detection of strabismus using the Hirschberg test that achieved 94 % accuracy in classifying individuals with or without strabismus. The images of 45 patients in the primary position (PP) were used. In this work, we propose to calculate the deviation in the diagnostic gaze positions: primary (PP), upward gaze (SUPRA), downward gaze (INFRA), right side gaze (DEXTRO), and left side gaze (LEVO), and provide the syndromic diagnosis of strabismus for each patient. The checking of the alignment in the five gaze positions provides useful information for the planning of surgical strabismus treatment.

We introduce another important change in the protocol of image acquisition by including patients with deviations greater than 15Δ and up to 90Δ, as opposed to the methodology in [1] that was limited to detect deviations in patients of up to 15Δ. The previous research sought to detect deviations that could not be visually identified, proposing only the preliminary checking of the patient, while our study intends to serve both for preliminary checking and aiding in the diagnosis.

Materials and Methods

Patients

The images used in this study belong to patients from a private eye clinic located in the city of São Luís, MA, Brazil. The images database is constantly updated with the introduction of new patients who wish to collaborate and that satisfy the criteria described in the next section. The patients who volunteered to participate in the study signed a consent form, and approval from the ethics committee was obtained for the use of human images in this study.

Acquisition Protocol

The patients underwent an acquisition protocol defined by a specialist physician that established criteria for the inclusion and exclusion of patients from the database. The patients belonging to the database were examined by observing the visual acuity, biomicroscopy,[2] fundoscopy[3] (posterior pole), applanation tonometry[4] (when possible), and ocular motility exam[5] by means of the Cover test to detect the presence or absence of deviation.

The exclusion of patients from the study was done according to exclusion criteria, such as presenting deviations below 90Δ horizontally or vertically, opacity or any other alterations in the cornea, irregular contour of the limbus, microphthalmia,[6] perceivable nystagmus,[7] incapability of achieving 1.0/1.0 on the Snellen table,[8] and incapability of reaching 40$''$ of arc in the Titmus test of stereoscopic visual acuity.

Image Acquisition

Image acquisition was performed at the eye clinic using a camera *SonyR Cyber-shot* 8.1 megapixels, 3x optical zoom, set to image capturing mode (to provide clear and more detailed image) with 2048×1536 pixel resolution.

The pictures were taken with the patient seated in the examination chair. The room light remained on with no additional light focus. The patient was asked to look at an accommodative figure laterally attached to the camera lens. The *flash* was switched on to generate brightness or the first Purkinje image.[9] The macro function was used to ensure perfect focus of the acquired image, even when the

[1]Differential diagnosis is a method to distinguish between two disorders of similar appearance.

[2]Biomicroscopy provides a view of the exterior of the eye (cornea, sclera, and conjunctiva), the components of the internal chamber (the iris, aqueous, lenses, and their capsules), and even part of the posterior segment (anterior chamber, vitreous, and retina) by means of a suitable lens.

[3]The fundoscopy is an exam of the fundus of the eye.

[4]The tonometry is a measurement of the intra-ocular pressure.

[5]The assessment of the ocular motility is performed by means of the cover test (of the manual occluder) or by the corneal luminous reflection, in which the patient stares at a point (cover test) or light (luminous reflex) to check the deviation of the eyes when looking at near and distant objects.

[6]Alterations in the size of the eye.

[7]Nystagmus are involuntary and repeated rhythmic movements of one or both eyes in some or all view directions.

[8]The Snellen table, also known as Snellen's optometric scale, is a diagram used to assess the visual acuity of a person.

[9]Virtual image located behind the pupil [23].

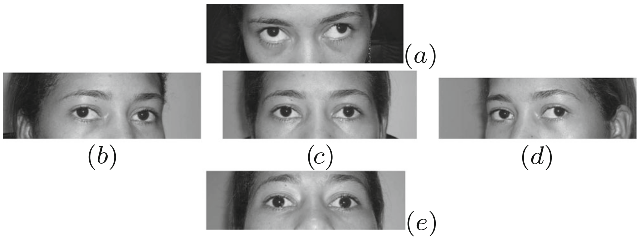


Fig. 1 Images in the 5 gaze positions: **a** SUPRA, **b** DEXTRO, **c** PP, **d** LEVO, **e** INFRA

patient was approximately 40–50 cm from the camera. If the patient used corrective lenses, the pictures were taken with the patient wearing them. For each patient, five images were taken in the following positions: PP, LEVO, DEXTRO, SUPRA, and INFRA.

To guide the tilt angle and rotation of the patient's head to the standard values of the diagnostic gaze positions, a ruler and a protractor were used to guide the patient's gaze to the desired position.

The image database in [1] was formed by 45 patients photographed only in the primary gaze position (PP). In this work, 200 new images from 40 patients of both sexes and varied ages, with or without corrective lenses, were used. Figure 1 shows the gaze positions to which the patients were submitted.

Proposed Methodology

Strabismus diagnosis by means of digital imaging depends on the generation of accurate limbus and brightness locations from the images. To attain such, the proposed method is organized in five steps, as shown in Fig. 2. The face images of patients were manually blurred at the upper and lower parts to protect the identities of the subjects shown in this paper.

The first step is to reduce the search space by eliminating the background using face segmentation. Once this is done, the eye region is detected to exclude face regions that are not part of the method. Precise eye location is then performed to further restrict the search space. The limbus and brightness locations are generated, and the strabismus syndromic diagnosis is made. The next sections are devoted to a detailed description of the above listed steps.

Face Segmentation

The face segmentation initial step aims to eliminate the existing background and fix the boundaries of the face area that will be used in further processing. The method starts with the image acquisition followed by its redimensioning from 2048×1536 pixels, to a resolution ten times lower of 205×154 pixels, to minimize the image processing computational cost. This reduced image is only used until the eye location step is completed, as the limbus location step requires an image with better resolution so as not to miss image data.

The image is converted from the RGB color type to YCbCr to derive the map of skin color. Skin detection allows face segmentation based on the pixel intensity that most closely resembles the color usually presented by the skin. For face segmentation, the same map of skin color as proposed by Chai and Ngan [3] is used.

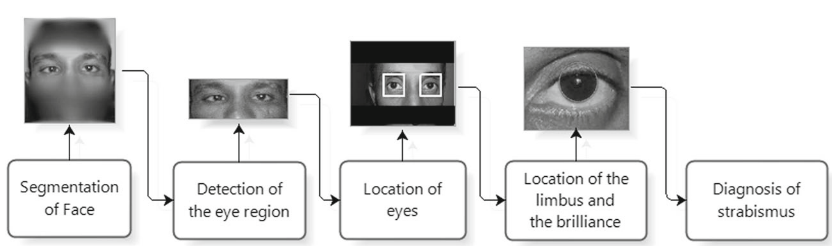
Detecting the Eye Region

This step aims at reducing the search space in the image of the segmented face to generate a sub-image containing only the possible eyes region, while excluding regions of no interest (such as the mouth, nose, and hair) to simplify the next step of eye location.

The image redimensioned in the previous step is converted from RGB color to grey gradients because it is computationally simpler and more efficient to work with one color channel than with three. After the conversion, homomorphic filtering [18] is applied to solve light divergences. Image smoothing is performed using a 3×3 mask Gaussian filter, and the input image gradient, generated in the previous step, is calculated using the Sobel filter [10].

A horizontal projection of that gradient is applied, resulting in the average value of the three major peaks of that projection. It is important to know that the eyes are in the upper part of the face and that, together with the eyebrows, they correspond to the two peaks close to each other. This physiological information, known a priori, can be used to identify the area of interest, and the peak of the horizontal projection will provide the eyes horizontal position. To eliminate interferences from the upper regions of the hair and mouth, the projection is applied starting from 1/5 to

Fig. 2 Steps of the proposed method in this study



1/2.5 of the height of the face image. The area of the eyes region has the same width and 1/3 of the height of the image segmented in the previous step.

Location of the Eyes

Using pattern recognition techniques, eyes location is determined in two steps, training and testing using the approach introduced by Almeida et al. [1]. In the training step, a classifier for each eye-gaze pose is created, and in the testing step, the samples are classified using this classifier. To train each classifier, 1050 samples from 35 images of patients were selected, with 18 regions of the eyes, 9 for each of the right and left, and 12 regions of other face areas for a total of 30 samples of 30×30 pixels.

Samples are automatically detected using Houghs transform based on the orientation annulus operator [7], which was applied for locating right and left eyes candidates using radius intervals[10] varying from 4 to 10 pixels. For each eye, we extract the six coordinates that have the most votes in the accumulation vector of the HT.

Eye candidate samples undergo pre-processing using histogram equalization [10]. Next, they are submitted to a texture characteristics extraction step. This study uses geostatistical functions [1] to describe the texture of objects that represent the eyes and other face areas taken from faces images. In [1], the best classification results were obtained using a combination of four geostatistical functions, semivariogram, semimadogram, correlogram, and covariogram, generating a total of 832 characteristics. Thus, this approach will be used to generate the characteristics vector.

The application of the oriented annulus requires the computation of the partial derivatives in the components in X and Y. The results of both derivatives are summed, and the resulting image represents the accumulator of the Hough transform. The higher the value in a position, the higher will be the chance that this position represents the center of a circle and, consequently, the center of an eye candidate.

The characteristics extraction performed by the geostatistical functions yield several variables that enable the selection of characteristics that better distinguish the classes eye and non-eye (other face areas) using the discriminant analysis stepwise technique [16].

The final stage is classifying each object as eye or non-eye using pattern recognition techniques. The method proposed uses support vector machines (SVM) [4]. The eyes are considered to be localized as soon as the first sample, among the top six on each side (right/left), is classified as eye. If the eye is not located among the top six, the search continues within the other candidates in the accumulation vector.

If, after the first iteration, the method cannot locate at least one of the eyes, it may mean that the eyes are not in the image of the eyes region. Thus, the former process is repeated, fixing the Y coordinate by adding the current value plus half the height of the eyes region. The window is shifted from top to bottom until at least one of the eyes is located or until there are no more pixels to be checked.

Locations of Limbus and Brightness

Our method uses the automatic Hirschberg test, starting from the patient's photography, to generate the reflex location that verifies the alignment of the two eyes. To do so, the Canny method was applied as an eye edge highlighting technique, and the Hough transform (HT) was applied to contour the limbus region.

In this step, the first acquired image is redimensioned to a resolution of 1229×922 pixels to minimize the computational cost of the image processing without losing details of the limbus edge. Next, pre-processing is carried out using the Smart Blur filter [12] to eliminate noise, blurring parts of the image while preserving the edges. After this pre-processing, the images are then converted from RGB to gray levels.

The eye coordinates found in the previous step are redefined to find the values corresponding to a 1229×922 resolution. Next, Canny's method is applied using a 1.2 derivation factor, the 5×5 mask used in the Gaussian function, and lower and upper limits of 100 and 136.

The HT technique is used to determine the limbus edge locations. This technique uses the edge map generated in the previous step. Points at intervals from 0 to 60° and 300 to 360°, corresponding to an opening of 120° on the right side of the circle drawn at the edge points, and from 120 to 240°, corresponding to an opening on the left side were considered. Notes side of these intervals were excluded from the accumulation vector to limit the influence of the eyelids on the limbus location. The limbus edge was located using radius intervals varying from 22 to 55 pixels where, from which were selected the 80 highest rated coordinates within the accumulation vector, ordered according to the vote. The most voted coordinate is selected and, if there are others that received the same number of votes, the one with the smallest radius is chosen to ensure the selection of a circular region. This process is done for both the right and left limbi.

Once the two candidates for the limbus are obtained, called right (Ld) and left (Le) limbus, with radii of Rd and Re, respectively, we checked if the difference between Rd and Re is greater than 2 pixels. If so, the lower is taken as a reference. If Rd is the smaller, we seek within the most voted candidates in the Le accumulation vector the first radius

[10]Radius intervals used in this work were determined by analysis performed in the image bank used in the tests.

with a maximum difference of 2 pixels with respect to Rd. If there are more peaks with a radius equal to Re, we choose the one an alignment closest to the Ld horizontal axis to ensure the accurate location of both limbi.

Initially, the HT was applied to detect the center of the limbus radius in both eyes of the enclosed image. Next, the HT is applied again within the previously detected region to locate the reflection center. To locate the brightness, radius intervals from 2 to 4 pixels were used, considering all points of the circles drawn in the edge map and projected into the Hough's space (accumulation vector). The 80 most voted coordinates within the accumulation vector[11] are then selected and ordered.

For example, the right eye brightness location is verified, among the six top peaks in the accumulation vector, as being closest to the right limbus center, so as to ensure that the limbus location does not fall in the eyelid region when the eyes are half open and to avoid confusion with reflexes generated by corrective lenses. That procedure is used to locate the brightness of the right and left eyes.

Strabismus Detection and Diagnosis

The detection of strabismus uses the location of the corneal light reflection or first Purkinje image generated by the Hirschberg's test and the limbus location as parameters for checking the alignment of both eyes.

As the goal of this study is to develop an easy, fast, and cheap way for automatically evaluating whether a person is likely to suffer from strabismus that is accessible to general ophthalmologists not sub-specialized in strabismus, any method that requires mensuration of the Kappa[12] angle in each eye, keratometry[13] or keratoscopy,[14] or the axial length of each ocular globe, as done in other works [11, 20], is not feasible. The maximum admissible would be to consider the refraction of each eye when analyzing the images, as this is a basic data that can easily be checked by any ophthalmologist.

In the study published by [1], the strabismus is detected using only deviation values in pixels and by setting cutoff points or thresholds of up to 1 pixel of vertical deviation and 2 pixels of horizontal deviation for a patient to be considered normal. This study, on the other hand, used deviation in prismatic diopters (Δ), the unit used by strabismus experts to measure deviation.

[11] That amount was chosen after performing some tests.

[12] Angle formed by the optical axis and the gaze line.

[13] Computerized examination to measure the corneal surface curvature.

[14] Keratoscopy or computerized corneal topography is an examination through which a qualitative and quantitative analysis of corneal astigmatism may be performed.

The assessment of the first Purkinje image position in each eye is done in the following manner:

1. The distance from the reflex center to the limbus center in the vertical and horizontal directions in both eyes is measured, which are respectively called vertical (VD) and horizontal deviations (HD);
2. The average limbus horizontal and vertical diameters are, respectively, 11.46 and 10.63 mm [15]. Thus, conversion from pixels to millimeters (pixelMM) is performed using as a reference the average limbus diameter value (LD) of an adult of 11 or 12 mm.
3. Deviation is calculated, in millimeters, using the equation:

$$value = deviation \times pixelMM \quad (1)$$

4. Finally, the deviation value is converted to prismatic diopters using the conversion of 1 mm = XΔ.

The original equation suggests that each millimeter of brightness decentration with respect to the limbus center corresponds to roughly 13 to 17 Δ [13], but several studies report that the Hirschberg rate is between 21 and 22 Δ/mm for the measurement of ocular alignment [8, 19, 21]. Jethani [13] analyzed both the original value of 13 to 17 Δ as well as the value of 22 Δ/mm proposed in [8, 19, 21] and presented a value of for each deviated millimeter. Hence, as it is difficult to find an equivalent assessment value between deviation per millimeter and prismatic diopters, tests using values of 15Δ [22], 19Δ [13], and 22Δ [8] per deviated millimeter will be conducted.

Figure 3 is an example of the HD calculation in a patient with horizontal deviation. It may be noted that the limbus center is not aligned with respect to the brightness center.

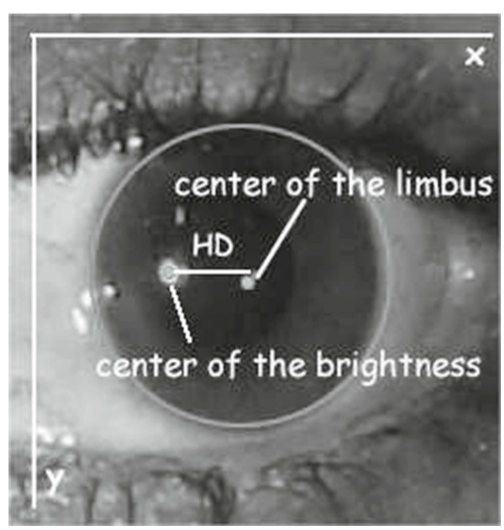


Fig. 3 Alignment calculation

After the identification of the fixating eye, the type of deviation in the impaired eye is checked. Strabismus can be classified as horizontal—convergent (esotropia) and divergent (exotropia)—or vertical—hypertropia and hypotropia. Strabismus is convergent when one eye grasps an image and the other turns inwards and is divergent when the other eye moves outwards. In hypertropia, one of the eyes turns upwards, while in hypotropia, the eye turns downwards. In all cases, each of the eyes focuses on a different image and the person becomes diplopic, having double vision.

A patient is diagnosed as esotropic (ET), or with convergent deviation in the non-fixating eye, if the horizontal coordinate (x axis) of the brightness is less than that of the limbus center; otherwise, the diagnosis is divergent deviation, or exotropia (XT). The same methodology applies to vertical deviations, which are checked by using the Y axis. If the vertical coordinate of the brightness is less than that of the limbus center (ET), the patient is diagnosed as hypotropic (HoT), while the opposite situation indicates hypertropia (HT). A patient can also present a horizontal deviation associated with a vertical one, such as having both ET and HT deviations.

A deviations can be referred to as comitant, when it has the same magnitude in any gaze position, or noncomitant, when the deviation varies at different gaze positions. For that reason, measures taken at positions PP, LEVO, DEXTRO, SUPRA, and INFRA will be adopted. Information provided in this step can be used by the specialist for treatment, prescription, and sketching of surgical planning.

Results

Face Segmentation

In the initial stage, from the 200 images of 40 patients, we observe that the face segmentation algorithm was effective in 88 % of the images, correctly delimiting the region of the face. In the other images, the segmented area additionally presented regions of the image background. For the purpose of testing, and to prevent the remaining 12 % of the images from being discarded from the other stages, we opted to keep these images for the next stages, as the region of the eyes was present in them. The only impact is that these images have a larger search area when the SVM classifier is applied.

Eyes Region Detection

By using the 200 images from 40 patients from the previous step, an average accuracy of 98.5 % was obtained for eye detection in the five gazing positions. Positions SUPRA and DEXTRO were 100 % accurate, while images in positions PP, INFRA, and LEVO were 97.5 % accurate. In the images that presented errors, the eye region was marked with centralized eyebrows while excluding the eyes.

Images that did not properly detect the eye region are subjected to the procedure described in "Location of the Eyes", in which a window is used to scan the image from top to bottom until at least one of the eyes is found or until there are no more pixels to be checked.

Eyes Location

Once the eye region is detected, the eyes location step is started ("Location of the Eyes"). In accordance with "Image Acquisition", the patient image database is comprised of 200 photographs. From these was formed the training data set presented in "Location of the Eyes", followed by the extraction and selection of characteristics and the SVM training. The best classification results of [1] were obtained by combining the functions corelogram, covariogram, semimadogram, and semivariogram, generating a total of 832 characteristics. Therefore, this approach will be used to generate the characteristics vector.

The stepwise discriminant analysis is used to identify the independent variables that best discriminate the classes, producing a reduced set of variables. Following the methodology proposed in "Location of the Eyes", the next step is the classification and validation of results. Using the images tested by the application of the proposed methodology, we achieved an eye detection accuracy of 96.25 % for PP and INFRA images, 92.5 % for DEXTRO, 97.5 % for LEVO, and 93.75 % for SUPRA, for a total accuracy of 95.25 %. Only the images in which the eyes were correctly detected pass to the next stage.

The final stage is to classify each object as eye or non-eye using pattern recognition techniques. This methodology uses a support vector machine (SVM) by means of the LIBSVM library [4]. The classifier is used with a radial kernel (RBF). There are two parameters that must be configured when one uses the RBF kernel: C and γ. We do not know what values of C and γ are most suitable for the problem, so a selection model (search parameters) must be built to identify the best C and γ so that the classifier can precisely predict the unknown data. To determine the optimal values of these parameters, we use the grid search technique, available on the LIBSVM library, which performs an exhaustive search in the parameter space on the training data. The estimated values for C and γ with respect to the radial center are presented in Table 1.

The eyes are considered to be located once the first sample, among the six largest, on each side (left/right) is classified as eye. If after the first iteration the methodology does not find at least one of the eyes, then the eyes may

Table 1 Parameters C and γ estimated by grid.py for training samples

	PP	SUPRA	INFRA	LEVO	DEXTRO
C	512	512	8	512	2
γ	0.03125	0.03125	0.5	0.03125	2

not be present in the image. In this case, the previous process is repeated after the adjustment of the Y coordinate by adding half the height of the eyes to its present value. In other words, the window will scan the image upside-down until at least one eye is located or until there are no pixels left to be verified.

Limbus and Brightness Locations

Success in strabismus location is directly linked with the limbus and brightness locations, as these locations are used in the alignment calculation ("Strabismus Detection and Diagnosis").

The highest accuracy for the limbus location was 96 %, for images in the SUPRA position. Images in the INFRA position presented more errors, obtain only an 84.41 % success rate. This low accuracy can be explained by the partial veiling of the eyes by the eyebrows.

The highest accuracy in brightness detection was for INFRA images, with 100 %. The lowest was 95.94 %, for DEXTRO images. The average accuracies for limbus and brightness detection were 91.58 and 97.35 %, respectively. Figure 4a shows samples of images in which the method successfully identified the limbus and brightness regions.

Figure 4b shows images in which the method failed at locating the limbus due to reflected light from the cameras flash on the patients glasses. In Figs. 5c, f, the error was because the limbus was not visible, making edge detection difficult. The limbus and brightness must be properly detected to pass to the last step.

Strabismus Diagnosis

This section addresses strabismus diagnosis of patients in the five gaze positions. One hundred fifty-one of the original 200 images (75.5 %) that successfully passed through the previous steps will be considered.

The primary position (PP) produced the greatest percentage of images, 82.5 %, to reach this point. The reason for its superiority is that there is no inclination of the head, so that the limbus presents a larger visible area. The DEXTRO position produced the smallest percentage of images for performing the diagnosis, 67.50 %.

Table 2 presents the results obtained for the identification of horizontal type deviation (ET or XT), vertical type deviation (HT or HoT), patients without deviations (ORTO), and fixating eye identification. The method was 88 % accurate in identification of esotropias (ET), 100 % for exotropias (XT), 80.33 % for hypertropias (HT), and 83.33 % for hypotropias (HoT). Accuracy in fixating eye classification was 83.45 %.

Per "Strabismus Detection and Diagnosis", tests were performed using the approximate value of an adult limbus diameter (LD) equal to 11 or 12 mm. We also tested the values 15Δ, 19Δ, and 21Δ in millimeter conversion for prismatic diopters (Δ/mm). The best results were obtained by setting LD = 11 mm and using a 15 Δ/mm configuration. Table 3 presents the results obtained when checking horizontal (HD) and vertical (VD) deviations for images at each position associated with the equivalent value of Δ/mm, considering LD = 11 mm.

In Table 3, it is possible to note that the best values were obtained using the 15 Δ/mm configuration. For this configuration, considering the computation of the horizontal deviation in the images which reached the diagnosing stage, the method achieved 93.34 % for the 30 images in INFRA, while in SUPRA it reached 77.41 % in 31 images. Analyzing the percentage of correct computations of the vertical deviations, we verified that the method achieved

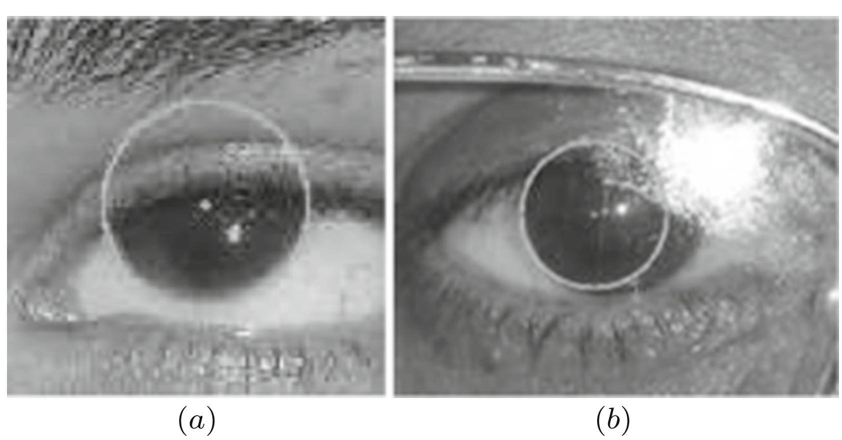


Fig. 4 Samples of images in which the method was successful (**a**) and failed (**b**) in limbus location

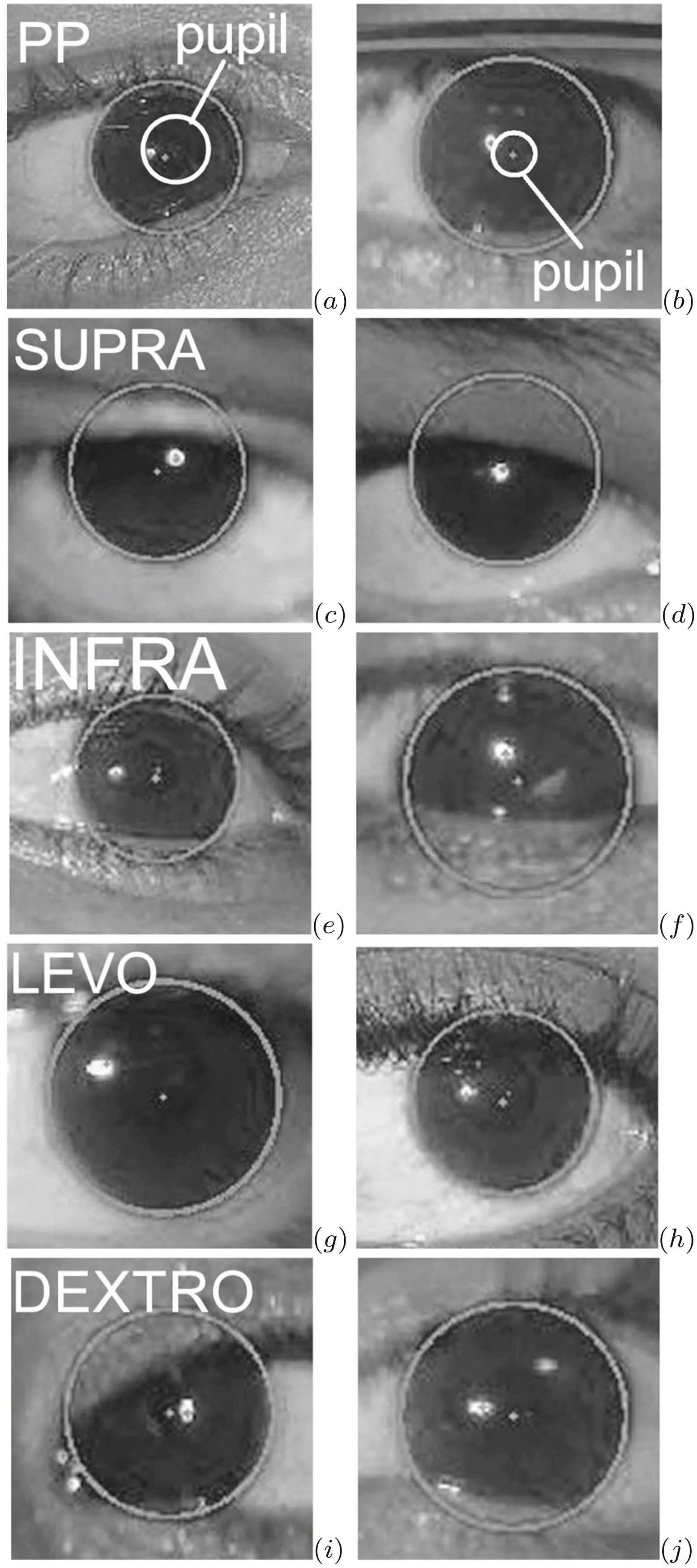


Fig. 5 Images of patients in PP (**a, b**), SUPRA (**c, d**), INFRA (**e, f**), LEVO (**g, h**), and DEXTRO (**i, j**) where the method failed in performing the diagnosis

Table 2 Diagnostic results when identifying horizontal (ET and XT) and vertical (HT and HoT) deviations of the fixating eye of patients with no (ORTO) deviation

	%					
	ET	XT	HT	HoT	ORTO	Fixating
PP	92.85	100	66.67	66.67	6.66	87.88
INFRA	100	100	80	50	19.23	90
SUPRA	83.34	100	100	100	8.82	74.2
LEVO	75	100	80	100	13.05	80
DEXTRO	88.89	100	75	100	8.34	85.2
	88	100	80.33	83.33	11.22	83.45

results above 90 % in all positions, highlighted by the DEXTRO image which obtained a result of 100 %. It is also possible to notice that on average (HdxVD), the method succeeded more in the images in INFRA and failed more in the images in LEVO. These failures can be explained by the difficulty at identifying and quantifying strabismus when the eyes are partially covered laterally (LEVO and DEXTRO). For DEXTRO, the percentage is better, but only 27 images reached the diagnosis stage.

Table 4 presents the number of images per gaze position that reached the diagnosis stage. Columns ET, XT, HT, and HoT represent the percentage of patients for each deviation type and primary position. It may be observed that most of the patients used in this study have horizontal deviations (ET and/or XT). According to the literature, horizontal primary deviations occur more frequently than other deviation types [6, 17].

In the PP position, the accuracy results in the calculation of horizontal and vertical deviations were 91 and 94 % using LD = 12 mm and 15 Δ/mm, respectively. The average error in prismatic diopters was 6Δ for HD and 4Δ for VD using the LD = 11 mm and 15 Δ/mm configuration. For LD = 12 mm, the methods average error was 5.72Δ and 4.3Δ.

Table 3 Result of the diagnosis using LD = 11 mm

	%					
	15Δ/mm		19Δ/mm		22Δ/mm	
	HD	VD	HD	VD	HD	VD
PP	88	90.9	82	90.9	61	87.9
INFRA	93.34	90	86.67	86.67	56.66	83.33
SUPRA	77.41	93.54	65	90.3	48	80.6
LEVO	80	90	67	80	57	80
DEXTRO	81.48	100	66.67	92.59	51.85	92.59

Table 4 Number of images that reached the final step and the percentage of patients with ET, XT, HT, and HoT

		%			
	Images	ET	XT	HT	HoT
PP	33	42.42	39.39	18.18	9.1
INFRA	30	40	50	16.7	6.67
SUPRA	31	38.74	35.48	6.45	9.67
LEVO	30	40	47	17	20
DEXTRO	27	33.3	51.9	14.8	11.1

Figure 5a represents the PP image of a patient who, according to the specialist, had 30Δ. However, the methodology diagnosed the patient with 15Δ ET. Deepened into the image, one can notice that the limbus edge is not centralized with respect to the pupil. The method failed to precisely detect the limbus edge because the patients limbus was only partially visible. On the other hand, Fig. 5b shows a patient who, according to the specialist, had 30Δ XT. Nevertheless, the method diagnosed him with 18Δ XT. It can be noted that this patient has his pupil clearly contracted with the diameter diminished. Usually, an adult pupils diameter is approximately 3 to 4 mm, while this patients pupil diameter is close to 2.5 mm. The greater the age of the patient, the greater the chance of this diminution occurring. Thus, the pupils edge would not be the proper reference for performing the Hirschberg test in this type of patient.

In the SUPRA position, the proposed method was 80.64 and 93.54 % accurate in the calculation of horizontal and vertical deviations, respectively, using the LD = 12 mm and 15 Δ/mm configuration. The average error was 6Δ and 3.62Δ for HD and VD, respectively, using LD = 11 mm and 15 Δ/mm.

Figure 5c represents the SUPRA image of a patient who, according to the specialist, has no deviation. The method diagnosed him with 17.84Δ XT and 1.54Δ HoT in the right eye. Deepening into the image, one can perceive that the limbus is partially visible and that the limbus edge is not centralized with respect to the pupil. The method may have failed in precisely detecting the limbus edge. Figure 5d presents a patient who, according to the specialist, had 20Δ ET in the right eye. However, the method diagnosed him with 4Δ XT in the left eye, while also failing in identifying the fixating eye. Similarly, in Fig. 5c, the limbus is not entirely visible. One can also notice that the light reflex is generated close to the pupils center.

In INFRA position, the best result was obtained using the LD=11 mm and 15 Δ/mm configurations. The average error was 5.11Δ and 4.28Δ for HD and VD, respectively. According to the specialist, the patient in Fig. 5e has 55Δ XT and 6Δ HoT, while the method diagnosed him with

39.72Δ XT and 2.27Δ HT. In the image one, can notice that the brightness is close to the pupils edge and the upper and lower edge of the limbus are not visible.

In the LEVO position, the smallest average error was 5.9Δ and 4.3Δ for the LD = 11 mm and 15Δ/mm configuration. The patient in Fig. 5g was diagnosed by the specialist as having 50Δ XT. However, the method detected 44.08Δ XT and 22.11Δ HoT. In Fig. 1, one can notice that the limbus is not centralized with respect to the pupils edge and the upper portion of the limbus is below the eyelid. Hence, that error would not have occurred if the detected limbus were close to the pupils center. In Fig. 5h, one can notice that the brightness is in the pupils edge, and yet, the specialist diagnosed it with 25Δ XT, while the method identified a 36Δ XT deviation.

DEXTRO images attained lesser accuracies in both eyes location and brightness detection. In this position, the average error was 5.11Δ for HD and 2.97Δ for VD. In the calculation of horizontal and vertical deviations, accuracies were 81.48 and 100 %, respectively, with a LD = 11 mm and 15 Δ/mm configuration.

The patient in Fig. 5i was diagnosed by the specialist as having 35Δ ET. Nevertheless, the method detected 14.56Δ ET and 4.46Δ HoT. In Fig. 1, one can notice that the brightness lies in the pupils edge and that less than half of the limbus edge is visible. Thus, the method may not have been accurate in the limbus location, and the specialist may not have noticed the brightness in the pupils edge. In Fig. 5j, we have a patient who, according to the specialist, has 35Δ XT, while with the method, he has 22.3Δ XT. Getting deeper into the image, one can notice that the brightness is inside the pupil.

For the images that reached the diagnosis step, after computation of the average errors in the five positions, the overall average error was 5.6Δ and 3.83Δ for HD and VD, respectively.

Discussion

In this work, tests were performed through each of the steps proposed in the method. All evaluations, except the strabismus diagnosis step, were performed visually, with an expert analyzing each image and determining whether each step's resultant images were properly computed: verifying if the face was correctly segmented during step 1, if the eye region was correctly obtained in step 2, if the eyes were located in step 3, and if the limbus and brightness were located in step 4.

The face segmentation step was 88 % accurate in the face segmentation and background exclusion. However, all 200 images passed to the next step because the eye region was present in all segmented images. Most errors that occurred in this step were caused by the presence of the expert's hand fixing the corrective lenses of patients who used them. Even when they are part of the protocol, as specified in "Acquisition Protocol", this type of interference can happen routinely, especially when the image acquisition is performed by non-specialists outside the clinic. Therefore, it was decided to include these images to address these limitations and evaluate the method's performance in these situations.

In the eye region automatic detection step using the projection in the magnitude of the gradient, accuracy was 98.5 % for patient images. Images without proper detection of eye region still passed to the next step, transferring responsibility to the eye location step.

In the eye location step, SVM classifiers were generated for each set of images of the gaze position. The generated classifiers were used to check if a given region of the image contained one of the eyes. At this step, the average accuracy of the method was 95.25 % for the eyes location. Only the images that had the eyes properly detected proceeded to the next step. For the limbus and brightness location step, Canny's method and Hough's transform were used with average accuracies of 91.58 and 97.35 %, respectively. Here, it was concluded that errors in the limbus location were mainly caused by light reflection from corrective lenses and by the fact that the limbus boundary, in some images, are not totally visible, hindering the limbus location determination through Hough's transform.

The method's accuracy was evaluated by comparing to the diagnoses presented by the specialist. However, the application of the Hirschberg's test by several specialists can yield different results. Choi and Kushner [5] assessed the precision of 17 experienced strabismus specialists when applying the Krimsky and Hirschberg tests for deviation estimation. The accuracies varied from 5 to 10Δ. Hence, because of the subjectivity of the Hirschberg test, we used a $\pm 10\Delta$ error tolerance to assess the values estimated by the method against those of the specialist.

In the diagnosis step, the method accuracy was 88 % in esotropias identification (ET), 100 % in exotropias (XT), 80.33 % in hypertropias (HT), 83.33 % in hypotropias (HoT), 11.22 % in ORTO, and 83.45 % in the classification of the fixation eye. The overall average errors were 5.6Δ and 3.83Δ for horizontal and vertical deviations, respectively, with respect to the measurements presented by the expert. The best results were obtained by using an LD = 11 mm and 15 Δ/mm configuration.

The low accuracy in the diagnosis of patients (ORTO) with no vertical and/or horizontal deviations (Table 2) can be explained by the proposed method's degree of precision with respect to the evaluation performed by specialist, who usually checks the deviations in 5Δ multiples, not considering small shifts, thus diagnosing the patient as ORTO.

Additionally, the specialist hardly works with a precision of 1Δ, and, when using the Hirschberg method, will hardly obtain such precision. Usually, the specialist checks all even values smaller than 10Δ (2Δ, 4Δ, 6Δ, and 8Δ), while for deviations greater than 10Δ, multiples of 5Δ are checked. Therefore, it is not possible to assert that the proposed method had low accuracy when identifying patients with no deviations because in the work of [5], experienced specialists estimated deviations with average errors varying from 5Δ to 10Δ.

One of the factors that affected the results of the identification of the fixing eye, with an average correct identification of 83.45 %, are patients detected with small deviations by the methodology who were diagnoses as normal by the specialist. When the patient has a deviation in one eyes, the other one is the fixing eye, and when there is no deviation, both eyes fix. That is, the patients who were diagnosed with small deviations ($< 10\Delta$) by the methodology were classified with one of the eyes as the fixing one, while the specialist classified them as having fixation in both eyes because no deviation was detected by the specialist.

Conclusions

This work showed the feasibility of using such techniques as image processing, geostatistical functions, and support vector machines for strabismus automatic diagnosis in digital images through the Hirschberg method. The proposed method was organized in five steps: segmentation of face, eye region location, eye location, location of the limbus and brightness, and strabismus automatic diagnosis. Regarding this study, several contributions can be noticed.

The first contribution occurs at the eye location step through the inclusion of the face segmentation step, as with the changes performed in the detection of the eye region, it was possible to improve the eye location step proposed by Almeida et al. [1], minimizing the cases of the eyes being absent for the next step.

Another contribution was the calculation of the deviation in prismatic diopters in the positions PP, INFRA, SUPRA, LEVO, and DEXTRO. However, the major contribution was the creation of a method for automatic diagnosis of strabismus through digital images. The method checks the type and size of horizontal and vertical deviations.

The present study, due to its innovative character, presents some limitations, namely (1) the image database used is formed by 40 patients—one of the factors which hindered the augmentation of this base that the acquisition was performed by just one specialist; (2) the diagnosis of only primary strabismus; (3) the Hirschberg test is limited to patients who present tropias (perceptible ocular deviations) and with deviations up to 90Δ; (4) the execution of the Hirschberg test for distant vision (distances of approximately 6 m); and the results of the proposed method, which were compared to results verified by only one specialist. To enhance the reliability of the results, the patients database must be augmented, besides addressing the diagnosis given by the method and the diagnosis given by other specialists. The ideal case would be the patient being evaluated by several specialists. This was not possible, in this study, due to the difficulty in finding specialists in strabismus willing to contribute to this research.

With the objective of improving the proposed methodology, some resources may be added: (1) computation of the limbus diameter, replacing the use of the approximated diameter of the adult limbus, to make the diagnosis more precise; (2) extending the methodology to the detection and diagnosing of tropias using the Cover test, which is more precise than the Krimsky and the Hirschberg tests; (3) performing the Hirschberg test for distant sight (patient staring objects 6-m far); (4) assessing the method with a larger volume of patients with horizontal and/or vertical deviations; and (5) incorporating the method and a tool for the medical area for detection of patients with strabismus, enabling the computer-aided triage in locations that do not have specialists in strabismus.

The proposed method is simple and inexpensive to be applied. By using an ordinary digital camera and software implemented with the proposed method, it is possible to estimate deviations in non-cooperative individuals or in those with poor fixation. It also can be used in patients on whom the Prism method or the modified cover method cannot be applied.

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