Effects of Iris Surface Curvature on Iris Recognition

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Abstract

To focus on objects at various distances, the lens of the eye must change shape to adjust its refractive power. This change in lens shape causes a change in the shape of the iris surface which can be measured by examining the curvature of the iris. This work isolates the variable of iris curvature in the recognition process and shows that differences in iris curvature degrade matching ability. To our knowledge, no other work has examined the effects of varying iris curvature on matching ability. To examine this degradation, we conduct a matching experiment across pairs of images with varying degrees of iris curvature differences. The results show a statistically significant degradation in matching ability. Finally, the real world impact of these findings is discussed.

1. Introduction

The concept of iris recognition performance being affected by the three-dimensional shape of the iris is not new. In 2004, Daugman [1] postulated that using the iris instead of the face for recognition was advantageous because the face is a three-dimensional surface that actively changes shape. Contrary to the face, the iris was assumed to only change shape significantly in two dimensions (pupil dilation). As a result, the three-dimensional iris shape is not often considered as an important factor in same subject matching performance.

The neglect of this factor may be due to perceptions surrounding the imaging process. For frontal imaging, the three-dimensional iris surface is projected to a two-dimensional annulus in the imaging plane. Because of this, the small changes in shape along the direction perpendicular to the imaging plane have a reduced effect on the resulting image. This work aims to demonstrate that these small changes can have a measurable effect on matching performance.

This notion that small three-dimensional shape changes may have measurable effects on recognition performance is also not new. Initially, pupil dilation changes were thought to be well modeled by a linear stretching of the annulus, the rubber sheet model of Daugman [2]. Over time, this model has been shown to be inadequate to completely model the changes in the iris texture as the pupil dilates or constricts [3][4]. One reason for error in the rubber sheet model is that it cannot account for texture change due to tissue folding that can occur as the iris changes shape in the direction perpendicular to the imaging plane.

Iris curvature has a similar effect to that of pupil dilation and constriction. A change in the curvature of the iris will cause a three-dimensional shape change that will result in non-linear texture change when imaged in two dimensions. As a result, the standard rubber sheet model cannot accurately correct for these changes.

If iris curvature changes will alter the texture of the iris when imaged, are these changes known to occur in the average person? The answer is yes. The accommodation response is an attempt of the eye to focus at various distances by changing the shape of the lens. The change in lens shape will cause a change in the iris curvature as shown by Dorairaj *et al*. [5]. This mechanism will be outlined in Section 2.

Given that iris curvature changes are witnessed in the real world, this work seeks to probe the relationship between curvature changes and matching performance. Since it would be difficult to control for this variable in the real world, a method of simulating the underlying iris surface shape changes is proposed in Section 3. Using a data set obtained through simulation of many iris curvatures, a statistical analysis is performed to determine if an increased difference in iris curvature between two images will result in degraded match performance.

Finally, the simulated observations of the effects of this process will be related to real world acquisition scenarios. In this discussion in Section 4, the difficulty of controlling for the iris curvature variable will be explained. Possible aging effects related to iris curvature and loss of accommodation ability (presbyopia) will be discussed.

2. Visual Accommodation and Its Effect on Iris Curvature

Glasser [6] provides a general overview of the function of and mechanisms behind accommodation in *Encyclopedia of the Eye*. The relevant portions of [6] are summarized here. The cornea accounts for 75% of the refracting power of the eye. The other 25% is handled by the lens. The lens has a non-constant refractive index with the greatest refractive power at its center (not at the surfaces). The gradient allows for a large range of refractions that would not be possible from the shape of the lens alone. Accommodation occurs when attempting to focus on nearby objects, and the term is defined as the dioptric (refractive) increase in optical power.

An eye is unaccommodated when focusing at optical infinity (any distance greater than 6m is considered to be optical infinity). The amount of optical power needed by a system to focus an object at some distance is measured in diopters (D). It also refers to the vergence of light rays emanating from an object toward some focal point. For an object at infinite distance, the vergence is 0 D and for an object 6m away it is $\frac{1}{-6} = -0.16$ D. This value is low enough to be considered optical infinity. As an object is moved toward the eye, the vergence increases. The increase in vergence necessitates an increase in the optical power of the eye in order to focus the object.

In younger eyes, accommodation occurs through an increase in curvature of the lens. As the eye ages, the ability to accommodate lessens until it is completely lost. This condition is known as presbyopia. Because the posterior boundary of the iris surface contacts the anterior lens surface, the shape of the iris surface is changed when the lens shape changes. Pupil size may also change as the eye accommodates.

Changes in the shape of the iris surface in eyes undergoing an accommodation response are measured in Dorairaj *et al*. [5]. In this work, the authors model the iris shape by measuring the curvature of the iris surface. This measurement is detailed in Figure 1. The curvature of the iris is defined by the length of the semi-minor axis of an ellipse approximated by the anterior surface of the iris. Increases in curvature result in more rounded iris surface. Decreasing the curvature results in a flatter iris.

In the work of Dorairaj *et al*., each subject was asked to focus at a distant object for a period of time to accommodate their eyes to optical infinity. Measurements of the iris surface curvature across meridians were recorded. The subject was then instructed to focus on an object 0.5m away (about 20 inches). Measurements of the iris curvature were obtained the moment the subject focused nearby and at one, two, and three minutes after. The authors noticed an immediate decrease in iris curvature when the subject changed focus from far to near. This immediate decrease was then followed by a steady increase in curvature in the three minutes following the change in focus.

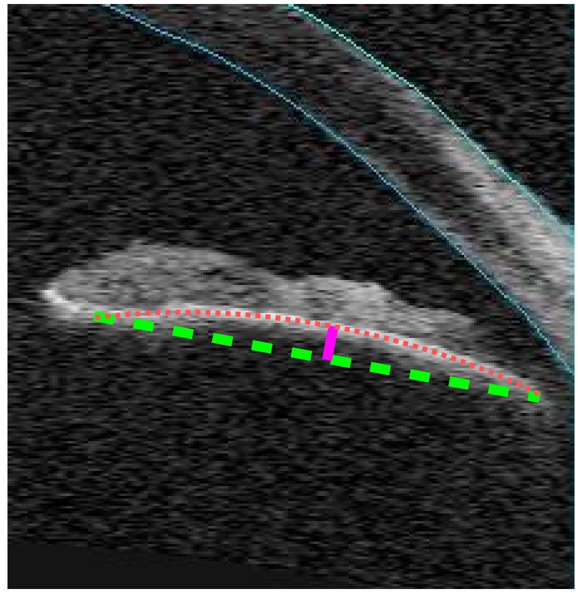


Figure 1: A measurement of iris curvature. The two most posterior points of the iris are connected to form the major axis of an ellipse (green dashed line). This ellipse roughly corresponds to the boundary of the posterior epithelium (red dotted line). The curvature measure is the length of the minor semi-axis of this ellipse (solid purple line).

The plot of the curvature with respect to time from [5] is shown in Figure 2 to illustrate the feasible range for curvature changes in the average person. The plot contains curvature information for three different groups each representing people with a specific type of iris. The narrow angle irises (NA) exhibit more curvature on average. Irises with pigment dispersion syndrome (PDS), a condition where pigmentation flakes off the bottom of iris and blocks the flow of the eye's fluids, are significantly less curved and are often slightly concave, and irises from the control group are slightly curved. Examples of these three types of irises are shown in Figure 3. Examining the data, it was determined that a maximum potential curvature change of 100 micrometers would be used for our simulations. This is a slightly conservative estimate. Thus, any negative effects observed in this range of curvature differences would likely be exac-

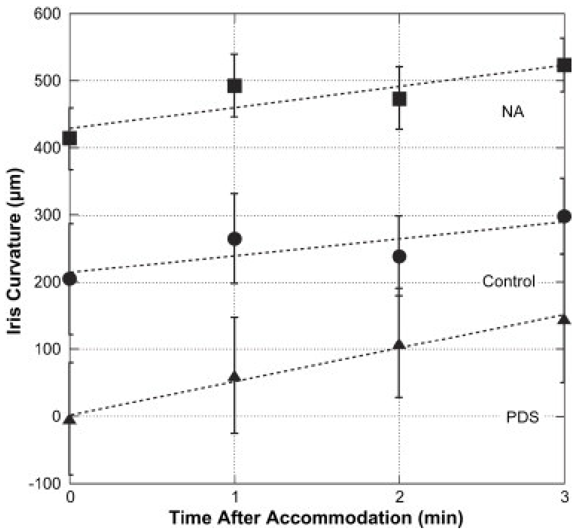


Figure 2: Rise in curvature following accommodation. Lines are linear regression with error bars. The three groups represented are narrow angle irses, irises with pigment dispersion syndrome, and normal irises.[1]

erbated in larger ranges.

3. Data Set and Experiment

As noted in [5], the iris surface may change curvature as the eye accommodates to change its refractive power. Given this information, we cannot assume that the curvature of a subject's iris remains constant between imaging sessions or even between subsequent images within one acquisition session.

An iris imaged at different times will likely not match itself perfectly. A number of factors may contribute to the deviation from an ideal perfect match including: camera focus differences between the images, motion of the subject, gaze of the subject, occlusion differences due to eyelids or eyelashes, angle of illumination, ambient illumination, and change in iris shape due to dilation or some other process. Given all of the variables possibly contributing to the deviation from ideal matching, it is difficult to measure the effect of any one factor on matching performance.

This difficulty is compounded because iris curvature is a three-dimensional deformation of the iris surface and cannot be measured from acquired two-dimensional iris images. It would be extremely challenging to acquire images for recognition and curvature measurements simultaneously for the same eye. Because this variable cannot be isolated and measured in a feasible acquisition scenario, simulation of the underlying process becomes an attractive option to measure the impact of iris curvature on matching performance.

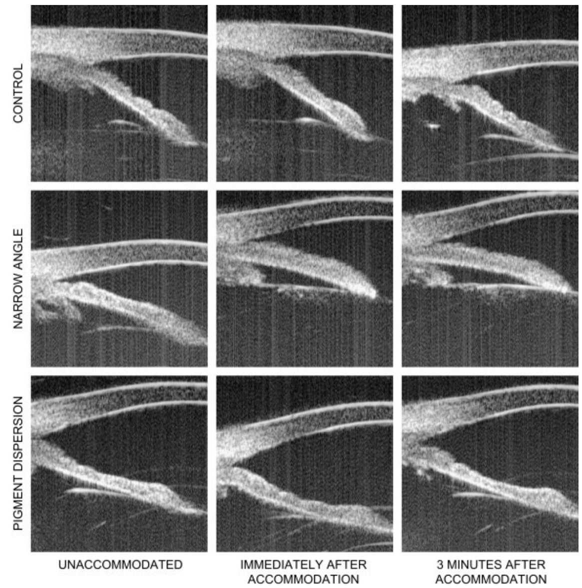


Figure 3: Ultrasound biomicrographs three groups of irises. The iris contour showed relatively little change for control (top row) and narrow angle (middle row) subjects following accommodation, but some increase in curvature over the subsequent 3 min (last column). For the PDS subjects (bottom row), posterior bowing was observed and increased (i.e., the curvature became more negative) after accommodation, followed by recovery over the next 3 min.[1]

3.1. Synthetically Modeling Changes in Iris Curvature

An anatomically accurate biometric eye model was proposed by Santos-Villalobos *et al*. [7] for use in estimating transformation functions to reproject off-axis iris images to frontal views while accounting for refractive effects caused by the cornea. The model is also capable of rendering realistic views of an iris at multiple angles by using ray tracing. This procedure is illustrated in Figure 4. However, the model as presented in [7] contains a planar iris instead of a dynamic three-dimensional iris surface. It must be extended in order to model the dynamics of surface curvature changes.

To generate the data set for use in these experiments, we implemented the corneal model of [7] and extended the iris surface constraint to allow for more general iris shapes. In this extension of the model, the iris surface is now measured by surface of revolution generated by revolving a cu-

[1]Reprinted from *Experimental Eye Research*, Vol. 86 / Issue 2. Syril Dorairaja, Cristiano Oliveira, Amanda K. Foseb, Jeffrey M. Liebmanna, Celso Telloa, Victor H. Barocasb, Robert Ritch. Accommodation-induced changes in iris curvature, pp. 220-225. Copyright 2008, with permission from Elsevier .

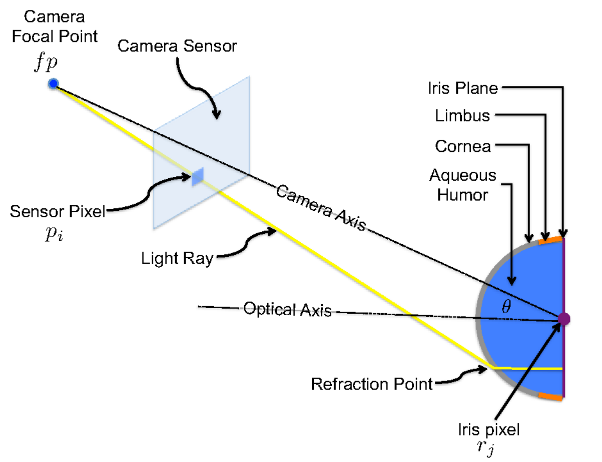


Figure 4: The ray tracing rendering procedure used to generate images of an iris with the model. Reprinted from [7].

bic spline about an axis (Figure 5). The model is imaged by rendering through ray tracing using POVRay 3.7 [8].

In order to adjust the curvature of the model's iris shape, the cubic spline representing the shape of the iris surface across a meridian (Figure 5) is changed. In keeping with the elliptical curvature model of [5], each point in the spline of the surface should be adjusted as if the surface were perturbed by an ellipse. This is accomplished by calculating the projection of each spline point onto the ellipse of iris curvature, P_E, and the projection onto the major axis of the ellipse, P_M. Let $V(A, B)$ refer to the vector connecting A to B. The spline point should be moved by the magnitude and direction of $V(P_M, P_E)$.

Given a candidate iris shape, changes in iris curvature may be simulated as follows (see Figure 1):

1. Define the major axis of the ellipse of curvature. (Green dashed line)

2. For a given curvature change (in micrometers), set the semi-minor axis of the ellipse of curvature equal to the curvature change. (Purple solid line)

3. Perturb each spline point according to its position on the ellipse of curvature. (Red dotted line)

4. Create the curvature adjusted iris surface by revolving the spline about the center of the whole iris.

The candidate iris surface shape can be derived from optical coherence tomography (OCT) images of an eye. The underlying image in Figure 1 was imaged using OCT. The OCT images give us little if any information about the accommodation state of the subject at the time of acquisition. Thus, both positive curvature changes and negative curvature changes are assumed to be possible. As a result,

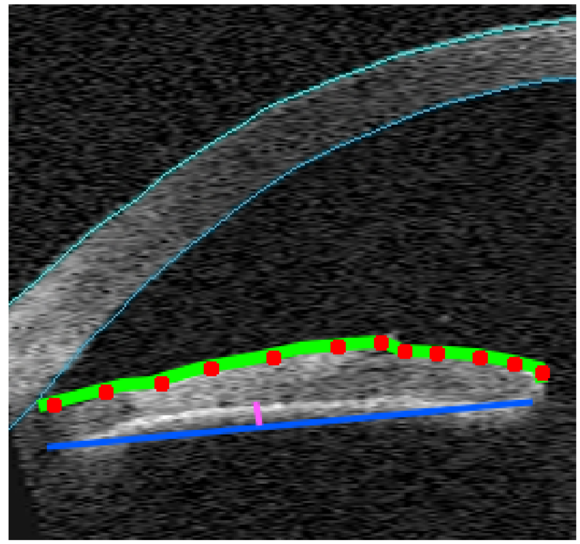


Figure 5: To generate an iris surface, cubic spline points (red) are defined on the iris surface curve (green) across a meridian. The spline is then revolved about the center of the iris to generate a 3-dimensional surface.

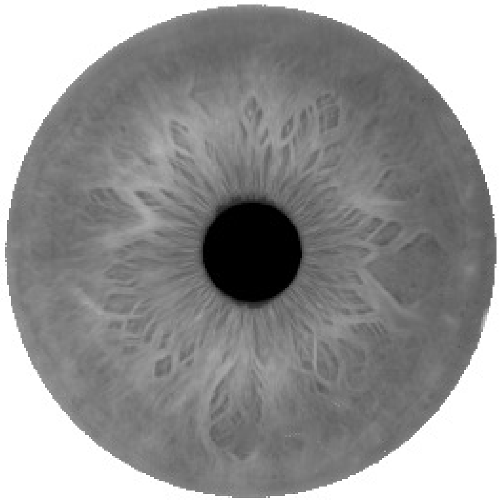
increasing and decreasing the curvature slightly will each yield reasonable iris shapes. To remain within the conservative limits proposed by [5], the *magnitude* of curvature changes generated by the model will be limited to 100μm.

Examples of images generated for the positive and negative curvature adjustments of 100μm are shown in Figure 6. In these images, only the iris curvature is changed. Every other factor is held constant including: eye position, camera position, occlusion amount (no occlusion in both cases), and pupil dilation level. Even at the extremes of the allowed curvature changes, visually, the images are almost identical.

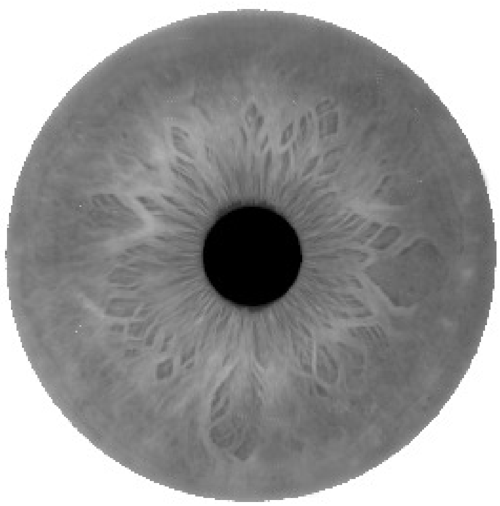
3.2. Data Set

The data set consists of 201 synthetically generated irises of a single subject. The iris texture itself is not synthetic, but comes from an actual imaged iris. What is synthetic, however, is the perturbation and rendering of the model. The generation of each iris begins with the same underlying iris shape which is then perturbed by a value in the range [-100,100]μm with a step size of 1μm. These irises are then imaged through ray tracing at horizontal gaze angles of [-5, 5]° in one degree increments generating 2211 unique iris images.

An all versus all comparison was performed using features generated from multi-scale Taylor expansion coefficients as found in the work of Bastys *et al.* [9]. These include quantized signals of the first and second derivatives of the rows and columns of the normalized iris image at different scales.



(a) Increasing curvature



(b) Decreasing curvature

Figure 6: Iris images generated by changing the curvature by 100μm

A matching similarity score is computed by comparing two quantized feature templates. The employed matcher is elastic and allows different shifts of the templates to be used for different sectors of the iris. This is done in an effort to account for non-uniform transformations of the iris texture. The scores of the matcher are in the range $[0, 1]$ with a score of 1 indicating perfect similarity.

3.3. Experiments and Results

This experiment is designed to test the hypothesis: an increase in iris curvature difference between two same subject images will result in a decrease in the match similarity of the two images. Using the all-versus-all match similarities from the data set, this hypothesis may be formalized in a statistical context.

If A represents the scores that come from matching irises with low curvature differences, and B represents matching irises with larger curvature differences, the original hypothesis may be reformulated into a one-sided Kolmogorov-Smirnov test with null and alternate hypotheses as follows:

$$H_0 : F_A = F_B$$
$$H_1 : F_B > F_A$$

F_A and F_B are the cumulative distribution functions generated from the scores of A and B respectively. The relation $F_B > F_A$ implies that distribution A takes on greater values than distribution B. Thus, rejection of the null hypothesis will show that a statistically significant difference in matching ability can be caused by iris curvature differences.

For this experiment, pairs of irises were placed into five curvature difference classes. These classes corresponded to the following difference ranges with the size of each class listed:

- $[12, 20]\mu$m (18315 pairs)
- $[32, 40]\mu$m (16335 pairs)
- $[52, 60]\mu$m (14355 pairs)
- $[72, 80]\mu$m (12375 pairs)
- $[92, 100]\mu$m (10395 pairs)

The score distributions and cumulative distribution functions of each of these classes are shown in Figure 7. The one-sided Kolmogorov-Smirnov test was then applied to each pair of distributions. If the original proposed hypothesis holds, then the defined null hypothesis of the Kolmogorov-Smirnov test should be rejected with p-values less than 0.05 when a class representing smaller curvature differences is compared against one with larger curvature differences.

The p-values for every pairwise test are shown in Table 1. Examining the p-values indicates that when distribution A is a score distribution for a class with smaller curvature differences than the class in distribution B, the null hypothesis is rejected. Thus, there is a statistically significant degradation in matching performance as the difference in curvature between two images increases.

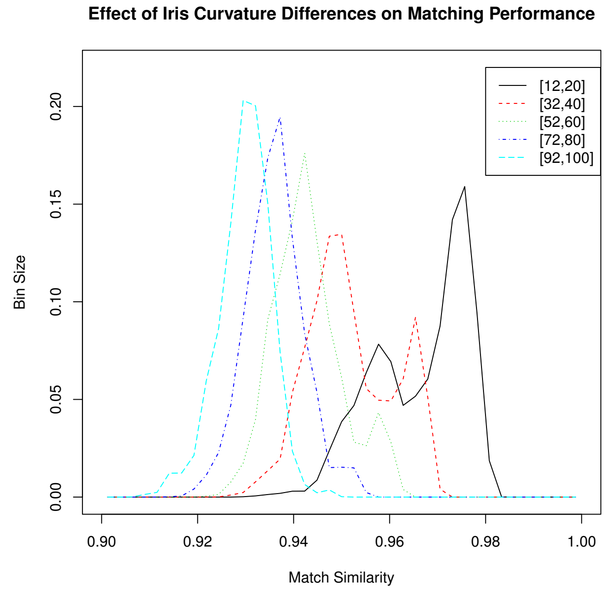
This trend may also be observed by examining a plot of match similarity score against the difference in iris curvature between the two images (Figure 8). From this plot, it is obvious that matching performance degrades as the curvature difference increases.

3.4. Discussion

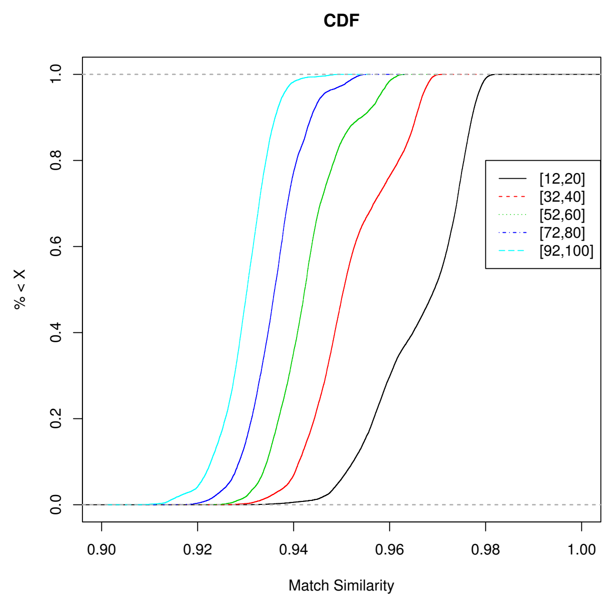
The results presented indicate that changes in iris curvature between images of the same iris can degrade matching

		Distribution A			
		[12,20]	[32,40]	[52,60]	[72,80]
Dist. B	[32,40]	0.000	1	1	1
	[52,60]	0.000	0.000	1	1
	[72,80]	0.000	0.000	0.000	1
	[92,100]	0.000	0.000	0.000	0.000

Table 1: p-values of the Kolmogorov-Smirnov test. Values less than 0.05 indicate the null hypothesis should be rejected in favor of the alternative.



(a) Score Distributions



(b) Cumulative Distribution Functions

Figure 7: The score distributions and cumulative distribution functions of each difference class

performance by a measurable amount. However, this experiment was only a simulation of biological effects. The question remains, are the curvature differences represented by the experiment likely to occur in the real world?

First, unconstrained iris acquisition scenarios will be discussed. This is followed by an examination of where these effects may arise in more constrained scenarios. Lastly, the possible effects of aging effects due to presbyopia (a loss of accommodation ability) will be discussed.

For the purposes of this discussion, the unconstrained recognition scenarios may encompass any scenario where the subject may be either far away from the sensor or not looking directly at the sensor. In either of these cases, it would be very difficult to determine precisely where the subject was looking. Thus, depending on where the subject is focusing, his eyes may be accommodated to any possible refractive power.

Because of this, it cannot be assumed that the accommodation power and thus iris curvatures are consistent in images acquired of the subject at different times. Because of this, even in the ideal case where frontal, completely in-focus, and unoccluded images were obtained at different times, the iris curvature effect may still inhibit performance.

Constrained scenarios are defined to be those where a cooperative subject approaches a sensor at a prescribed distance and gazes directly at it. This is the way many commercial sensors work. This scenario removes the issues due to off-axis iris capture, and greatly reduce camera focus variation.

Further, in these cases, because the subject is instructed to gaze directly at the sensor from a prescribed distance, the vergence of the object (the sensor) in the subject's focus may be accurately estimated. Also, the vergence of the object will be approximately the same for all subjects any time one approaches the sensor for acquisition. Because of this, it would seem reasonable that an individual subject would accommodate to approximately the same degree every time he approaches the sensor, but this cannot be assumed. The reason for this is that there is a time component to the accommodation response. As reported in [5], after the initial flattening of the iris, the curvature begins to return to the iris surface. Thus a very different iris curvature is likely presented if a subject were to turn to face the sensor after looking far away and have his iris quickly imaged versus waiting in a line while reading and then presenting his iris to the sensor. In essence, it would be very difficult to enforce constraints to hold this variable constant across acquisition

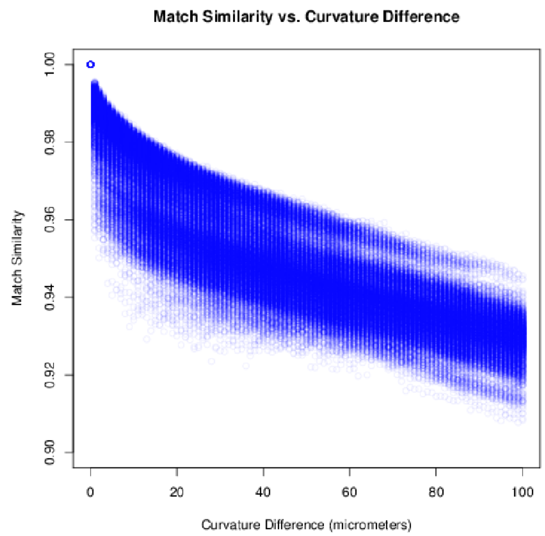


Figure 8: Behaviour of the match similarity as the iris curvature difference increases.

sessions.

Because iris curvature differences can impact match similarity, presbyopia may cause interesting effects in aging irises. For example, the amount of accommodative ability a person has decreases as he ages. At a certain point, the onset of presbyopia [10, 11], the lens is no longer able to accommodate. After this point, the person's iris should remain relatively constant with regard to iris curvature. Assuming otherwise healthy eyes, the results in this experiment would predict that true match scores among older subjects (post-presbyopia) should be better than those among young subjects due to the increased stability of iris curvature levels in post-presbyopic subjects. This prediction can be verified in future work.

Presbyopia may also contribute to negative aging effects of the iris templates. For example, assume that a subject's iris is enrolled at age 50, before the onset of presbyopia. At this age, the subjects iris is capable of a wider range of curvatures than after the onset of presbyopia. If the enrolled iris was captured in a severely curved state due to accommodation, then all matches after accommodation loss will be guaranteed to be suboptimal. Further, the slow loss of accommodation ability, and thus iris curvature range, could be a mechanism behind the observed negative effects due to template aging. Work in [12, 13, 14] documents the existence of the effect but does not provide a cause.

The existance and causes of the iris curvature difference effect have been examined but we do not yet know the relative impact of this effect compared to others such as pupil dilation. We suspect that the match degradations caused by iris curvature differences are quite a bit smaller than those caused by pupil dilation. It is important to note, however, that pupil dilation changes are connected with iris curvature changes in an accommodation response. Thus, is it as difficult to truly isolate the effect of pupil dilation alone.

4. Future Work and Concluding Remarks

In continuing this work, the next goal is to attempt to isolate the iris curvature variable as much as possible in real world data. This will likely be accomplished by emulating the scenarios discussed earlier. For the sake of completeness, an examination of the stability of the nonmatch score distribution with varying levels of iris curvature is needed.

This work may also be extended to the domain of off-axis acquisition scenarios. Given matching methods robust to gaze angle differences between images, interesting questions may be posed such as, "Are irises of a certain curvature more robust to off-axis matching scenarios?" Finding answers to that question may allow for the prediction of matching ability based on the subjects metadata (such as the presence of pigment dispersion syndrome).

This work presented a method to model iris curvature and synthetically generate data set of irises where only the curvature of the iris varied. With this data set, it was shown that even when imaged at near frontal horizontal gaze angles, larger curvature differences between two images can cause a significant degradation in match similarity. Finally, the probability of encountering differing iris curvatures in real world scenarios was discussed along with the explaining a possible correlation of these results to iris aging effects.

As a whole, this experiment indicates that, like pupil dilation, iris curvature is another change in iris shape that has the potential to negatively impact match similarity.

5. Acknowledgments

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