A new registration algorithm for estimating and discriminating average shapes of sets of corneal topographies

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***Abstract*— In this study we present a method to build 3D corneal atlases of different populations using a registration step based on inter-surface volume minimization. First the construction method is presented. It is based on a global factor computation in order to minimize the volume between several surfaces. Then the significance of the choice of the matching step is shown with the comparison of two atlases expected to be nearly identical: male vs. female corneas. Finally two atlases are presented and compared, for two different populations: right myopic and hyperopic eyes. Our study demonstrates that the matching step is crucial to correctly compare two surfaces, and shows two clinical applications of this method.**

I. INTRODUCTION

During an eye examination, it is common to measure the 3D corneal surface with a medical imaging technique called corneal topography. Some morphological changes may appear due to diseases, trauma, or surgery or simply due to aging. Therefore, analyzing such deformations may be useful for diagnosis. To distinguish a distorted cornea from a healthy cornea, it is necessary to specify what a healthy cornea is. The main difficulty of this specification arises from the significant variability within a population. A corneal anatomical atlas consists of a average surface and the variance around the surface. Usually, an anatomical atlas is built in two steps: matching several data from the same anatomical part and combining these data to compute an average.

The concept of the average cornea has been used in medical studies to compare several groups of different surgeries [1], of different age ranges [2], of subjects for a stability study of corneal topography in the post-blink interval [3], and for determining differences with the average model for a repeatability study [4]. In 2002, Buehren *et al.* studied the eye movement between successive topographies and introduced the notion of surface realignment to build a better average shape [5], using the *best fit sphere* (BFS) apex to adjust the xyz translations and a regression plane to rectify the tilt. Grzybowski *et al.* describe three different fitting zones: the apex point, peripheral, and global zones [6]. In 2007, Laliberté *et al.* [7] proposed a method to build a corneal anatomical atlas. The realignment step of topographies from different subjects is based on a *best fit sphere* (BFS) normalization. This method has been previously used in medical studies in 2012 [8]. Recently a more accurate method based on a registration step has been proposed to match corneal surfaces [9]. In continuation of this work, we present two clinical applications of this matching method for corneal atlases to show its accuracy compared to the gold standard BFS methodolgy presented in [7].

First, the atlas comparison and construction method are presented. Then to show how the matching step is important to compare two corneas, an exemple of comparison of two populations expected identical is detailed: male vs. female corneas. Finally two atlases are presented and compared, from two different populations: myopic and hyperopic eyes.

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II. CORNEAL DATA

The *Orbscan II* (Bausch & Lomb, Figure 1) is a topographer that acquires elevation points of the anterior and posterior surfaces, with an error margin of 1 micron. The data can be saved as a uniformly spaced 101x101 grid of elevations, spaced by 0.1 mm in X and Y.

Fig. 1. The *Orbscan II* (Bausch & Lomb) topographer

As the cornea is almost spherical, a smart and efficient way to visualize the global appearance of a corneal surface is to use a spherical reference, which makes it possible to study the differences from a sphere. First, we compute the BFS. Then, the difference between the corneal surface

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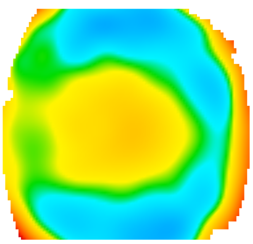
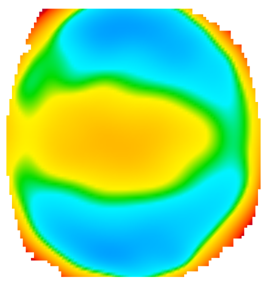
and the BFS surface is estimated at each point. Finally, each difference is associated with a color, using a standard colorset (commonly used by doctors for diagnostics), with warm colors for positive differences (points outside the BFS) and cold colors for negative differences (points inside the BFS). The colors are projected on a plane along the Z axis.

Figure 2 shows the construction steps of the colormap. Ophthalmologists commonly use this kind of map for diagnostic purposes.

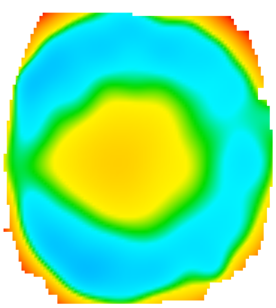
Figure 3 shows four corneal BFS maps of right eyes, taken from 4 different subjects with the Orbscan II topographer. We can see that the variability within a population is too high to represent a population with a single cornea. Furthermore BFS radii are slightly different, which explains why the matching step must include a scaling parameter.



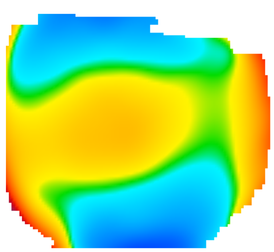
(a) BFS radius: 7.49 mm



(b) BFS radius: 7.87 mm

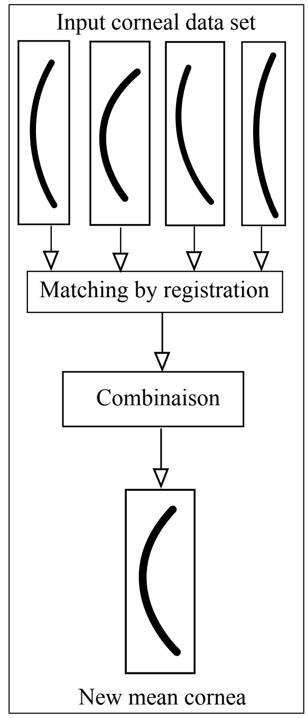


(c) BFS radius: 8.08 mm

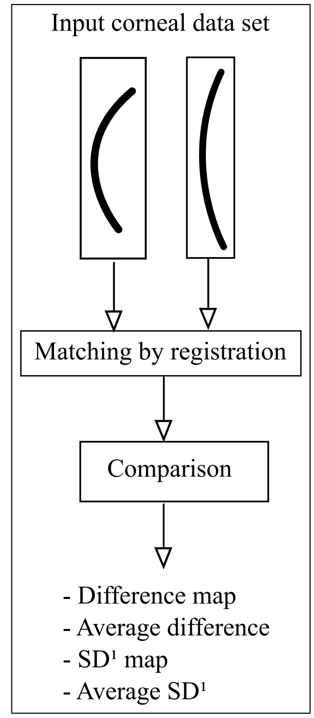


(d) BFS radius: 8.21 mm

Fig. 3. Four corneas from the Orbscan II topographer, anterior surface of right eyes of normal subjects



(a) Construction methodology



(b) Comparison methodology

Fig. 4. Methodology overview

III. ATLAS CONSTRUCTION AND COMPARISON

The matching or registration method used for construction and comparison is the same one, Figure 4 shows an overview of the full construction and comparison processing.

A. Matching step

The matching step is necessary to re-align surfaces that might be misaligned due to shape variability or eye movement during the corneal measurement.

This step uses a registration method based on a volume minimisation approach between two surfaces. As demonstrated in [9] this method allows a better matching than normalization to a spherical reference. To be realigned, surfaces can be translated, rotated and scaled during the process. A representative value of the volume is minimized: the average absolute difference (aad), which is computed as follows, with p_{s1} a point from the first surface, $s2$ the second surface, n_{s1} the number of points of $s1$, and $elevDiff$ the elevation difference from a point to a face:

$$aad = \frac{\sum abs(elevDiff(p_{s1}, s2))}{n_{s1}}$$

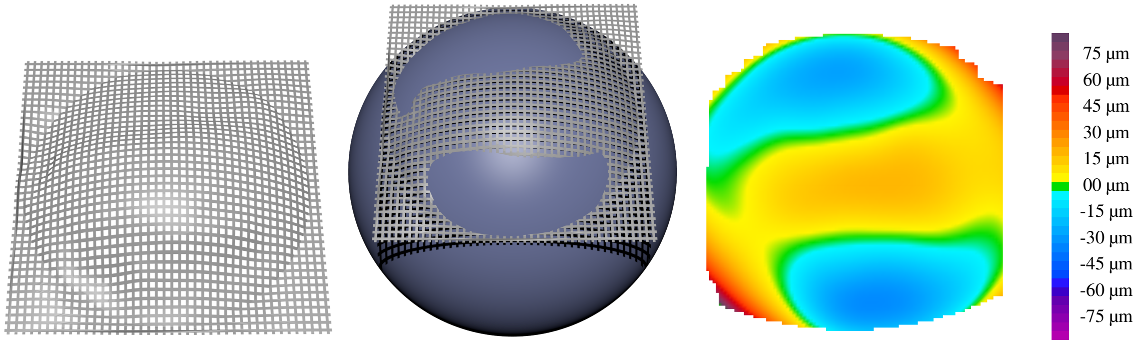
This value is iteratively minimized, to locate as close as possible both surfaces.

B. Combination

The combination step require to minimise more than two surfaces, to achieve that we minimize the *volume difference* between each corneal surface and a common reference surface (with the matching step previously described). At the beginning, the common surface is a sphere, and at each iteration a new average shape is built, resulting in a new common surface. At one point the common reference stops to evolve, meaning that the global volume minimization is achieved, and the surfaces are ready to be combined.

After the registration step, all re-aligned surfaces are resampled to a new common grid (using a bilinear interpolation). Then the new average surface is computed, additional statistics can be computed at this moment of the process (eg. SD[1] map, median shape).

[1] Standard deviation



(a) Heightmap (b) BFS Heightmap (c) Color map

Fig. 2. Best fit sphere color map building steps

By combining several surfaces, a new average shape is built, which later can be compared to other average surfaces or atlases or a to a single cornea (eg. comparison of a subject to a population).

C. Comparison

The difference between two corneal atlases (average surfaces) can be studied in several ways. Here, the difference is represented with a difference map and an average absolute difference (aad, described in *A. Matching Step)*. After the matching step, the difference map is built by subtracting one surface from the other. The average absolute difference can be used as a global similarity quantification, the closer to 0 this value is, the more the surfaces are similar.

IV. RESULTS

A. Matching test

To illustrate the importance of the matching step, we present an exemple where two populations expected to be identical are compared, namely corneas from male and female subjects.

Subjects were aged between 18 and 75 years. Atlases were built with right eyes Figure 5 shows difference maps (a) without matching step, average absolute difference = 6.8µm (b) with spherical reference (BFS) registration, average absolute difference = 1.9µm, with *inter-surface volume minimization* (ISVM), average absolute difference = 0.99µm. With the ISVM registration method, the matching process applied a scaling close to 1 (0.9997), this means that both corneas have the same size. The average absolute difference is close to the Orbscan II error margin, the difference varies from -3µm to +3µm in periphery, and is close to 0 in the central area, such variations are medically negligible.

Figure 5 (c) shows that matching with the ISVM registration method allows to refine comparison between groups.

B. Comparison of myopic and hyperopic eyes

To study two (expected to be) different populations we did a preliminary study on myopic and hyperopic eyes. Two atlases were built: using a myopic dataset of 271 right eyes (spherical equivalent of -5.0 ± 2.0) and a hyperopic dataset of 171 right eyes (spherical equivalent of 5.0 ± 2.0) aged from 22 to 70.

Fig 6 shows atlases (a) and (b), and the related difference map. Matching the myopic surface to the hyperopic surface required a scaling value of 1.0152 meanings that overall, the hyperopic eyes BFS (7.97 mm) was larger than that of the myopic eyes (7.86 mm). In other words, the hyperopic corneas were flatter than the myopic corneas. These results corroborate those from Llorente et al. [10]. Fig 6 (c) shows local anatomical differences between average myopic and average hypermetropic eyes, that could be interpreted as astigmatism differences between the two populations.

V. CONCLUSION

In this paper, we have demonstrated that a matching step based on 3D inter-surface volume minimization (ISVM) registration for the comparison of corneal surfaces gives better results than a simple spherical reference. We believe that this is because no a priori (spherical) shape was used for registration that could bias the alignment and therefore the atlas construction. Two case studies of population comparison were presented using this method, female/male and myopic/hyperopic.

With this methodology, a lot of applications are possible such as diagnostic assistance, by matching a subject to a group of pathologic atlases, or by quantification of differences from a normal healthy atlas. An atlas can be build as multiple sub-atlases, for each sub-group of a population. Thus it possible to compare a subject to each branch of a hierarchical atlas, in order to find out which one matches to the subject.

Another application we plan to develop is biometry to identify a subject based on the shape of his/her cornea after registration to a reference corneal surface.

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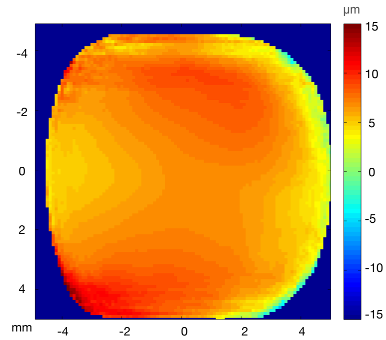
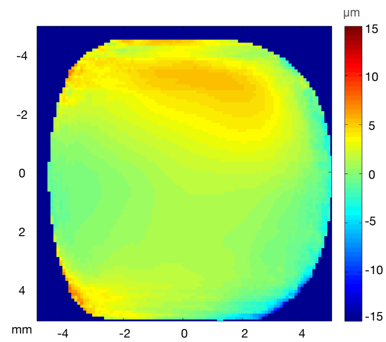
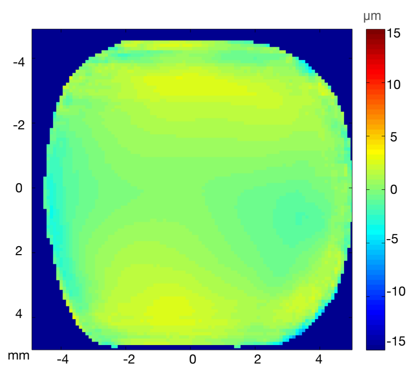


(a) Without matching step

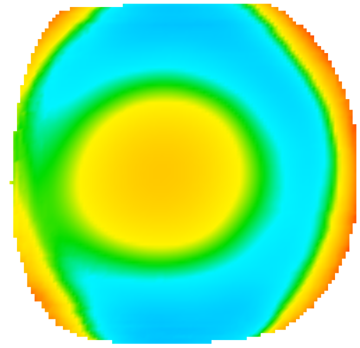


(b) With a spherical reference matching step

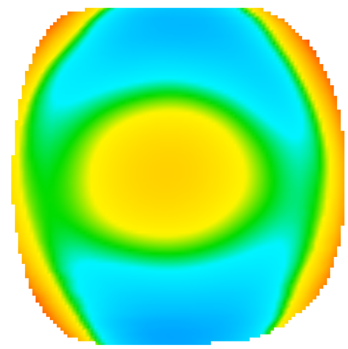


(c) With registration matching step

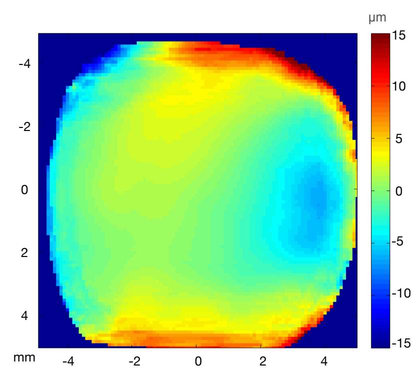
Fig. 5. Difference maps built with different matching step



(a) Atlas built with ISVM using hyperopic eyes, BFS radius: 7.97 mm



(b) Atlas built with ISVM using myopic eyes, BFS radius: 7.86 mm



(c) Difference map

Fig. 6. Myopic/hyperopic comparison result (Hyperopic - Myopic)

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