4D echocardiography, heart visualization, motion reconstruction

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HEART MOTION VISUALIZATION TOOLS FOR 4D ECHOCADIOGRAPHIC IMAGES

Qualitative and quantitative description of the heart wall motion is a very important field of investigation in modern cardiology. Abnormalities in heart motion are usually symptoms of life threatening cardiac dysfunctions therefore measurements of dynamic heart functions are of great clinical importance. The images of moving spatial heart structures can be efficiently acquired using 4D echocardiography. Unfortunately because of the low quality such images do not allow for precise measurements. To overcome this problem images need to be further processed and moving structures have to be extracted. In this work we present a method for estimating heart motion from 3D echocardiographic image sequence. On the basis of this method we have developed several visualization techniques that enable qualitative assessments of heart motions abnormalities. Together with quantitative measurements they may be become a useful tools in daily clinical practice.

1. INTRODUCTION

Ultrasonographic examination of the heart (echocardiography), together with techniques based on electrocardiography, is one of the most frequently used methods of the heart examination. Using this modality, vital information about morphology and hemodynamics of the heart could be collected by simple, bedside assessment. Echocardiography, even real time 3D, is relatively inexpensive (when compared to CT or MRI) data acquisition technique. In clinical practice the analysis of the data mainly relies on the visual inspection of the acquired views and on the physicians experience. Such methods lead to a qualitative and subjective assessment without taking into account individual quantitative information included in images. Another problem of the echocardiographic analysis are artifacts from the thorax (e.g. emphysema), which severely limits diagnostic value of echocardiography for 5-10% of patients. To reveal all these vital information and decrease information noise, automated computer-based analysis is highly desirable.

Several methods were proposed for the reconstruction of heart motion from 4D ultrasound images. For the left ventricle segmentation surface based methods (using shape and motion constraints) have been proposed to deal with speckle noise in the echocardiograms [2]. Biomedical models have been investigated for the modelling of

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cardiac cycle [3]. In this work we present a range of the heart wall visualization methods. These methods make an extensive use of the left ventricle motion description method [1] briefly presented in the next section.

2. HEART MOTION DESCRIPTION

Our reconstruction algorithm consists of few main stages. In the first step images are filtered using 4D anisotropic diffusion [4]. After that non-rigid registration of the 3D time sequence is performed to obtain the description of deformation field. Non-rigidly registered images are used to compute an average 3D dataset. The next phase consists of the shape and texture based segmentation followed by a triangulation step resulting in the 3D surface model. In the final step deformation operator is applied to the surface model in order to recover the time motion of the left ventricle.

In the first filtering stage (see Figure 1a) we deal with the time sequence of 3D ultrasound data. We have decided to take into account in the diffusion process also temporal consistency of the acquired data. The diffusion algorithm has been extended to the fourth dimensional block of data with the time taken as fourth dimension. As it was presented in [1] such filtering drastically reduces the speckle noise and enhances the structure boundaries. The speckle noise may lead to partial disappearing of the image boundaries. The time diffusion may help to recover some of the missing boundary parts.

In the second stage of our algorithm we describe the motion of the beating heart. It is important to model the motion taking into consideration individual patient specific anatomical features. In order to achieve realistic motion we have to extract heart dynamics by studying 3D movement of a corresponding anatomy between the reference frame (at time T_0) and the following frames ($T_1 - T_8$). We recover the transformation that aligns the reference frame with all the other frames using intensity based 3D volume registration (see Figure 1b). Such approach relies on an nonlinear transformation which allows to model local deformation of spatial objects. It is difficult to describe local deformation via parameterized transformations. The method of choice is usually FFD (free-form-deformation) method [5] which is commonly used as a powerful modelling tool for 3D deformable objects. The basic idea of FFD is to deform an object by manipulating an underlying mesh of control points. The manipulated lattice determines the deformation function that specifies a new position for each point of the deformed surface. The number of parameters to be optimised is equal to 3 times number of control points in the lattice. Because of a good localization of B-spline functions optimisation procedures can be applied locally. This allows for acceptable running times even for very dense lattices. In this work we use MSD (mean square difference) similarity function:

$$E_{MSD}(FI, RI, T) = \frac{1}{N} \iiint_{\Omega} \left(I_{RI}(p) - I_{FI}(T(p)) \right)^2 dp \,, \qquad (1)$$

where I_{RI} represents reference image intensities, I_{FI} represents corresponding transformed intensities of the floating image and N is the total number of overlapping voxels.

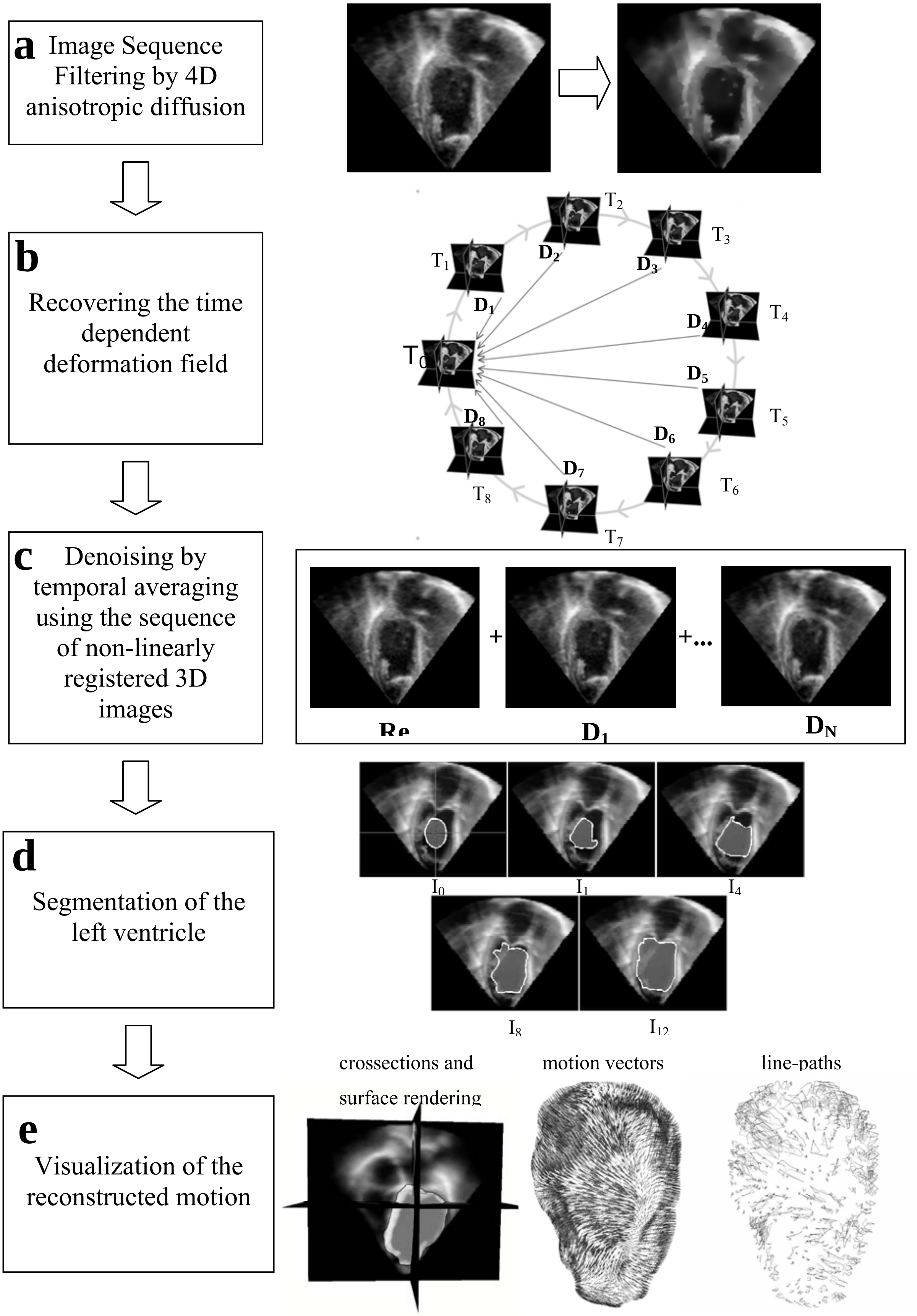


Fig.1. The flow diagram of our heart motion reconstruction algorithm.

In order to deal with large displacements in the registration process, we use a classical incremental multi-resolution procedure. After obtaining the 3D frames of the deformation field we are able to describe motion of the whole matter in the volume object.

At this point we are able to apply the second step of the denoising procedure using time averaging technique. The deformation fields are used to generate new datasets elastically aligned with the reference frame T_0. After this step an average dataset from the reference frame and all the deformed datasets are created (see Figure 1c). The noise located in the datasets is smoothed, while the boundaries of the image structures are preserved. When there is no noise correlation between time frames the process of averaging N frames results in decreasing of noise level $\sqrt{N}$ times.

After denoising procedures it is possible to perform the segmentation step (see Figure 1d) using the averaged dataset. In our work we decided to use an iterative deformable boundary approach for the segmentation of the ventricular inner surface. The selected method uses energy function consisting of texture based and shape based terms. It is a 3D extension of an algorithm proposed in [7]. Texture based energy term is calculated on the basis of texture intensity energy map which represents the probabilities of the intensity values i being consistent with the current segmentation model (updated in every iteration). This term has been formulated as the Shannon's entropy [6]. The shape energy term takes into account gradient information (revealed using Canny-Deriche's 3D boundary detection filter [8]) available in the source image. The main idea of this term is to deform (shrink or expand) segmentation model towards image boundaries. In this segmentation algorithm, starting from an initial estimate, a deformable model evolves under the influence of the defined energy to converge to the desired boundary of an image structure object. The model deformations are efficiently parameterised using the B-spline based Free Form Deformation.

After the segmentation procedure we create a triangulated surface representing our object of interest. At this point we are able to reconstruct the cardiac motion by applying the deformation field operator. In most heart visualization approaches presented in literature the motion of the left ventricle is described as a set of separated segmented objects. Our approach gives us a single geometric object deforming in time. Such approach has an important point-to-point correspondence feature which allows interpolation between deformation field frames in order to obtain smooth motion. At this point we may use various visualization techniques (presented in the next section) in order to enable precise qualitative analysis of the heart's motion. In the proposed method we obtain only representation of the inner ventricular surface so we can not calculate all the global parameters (i.e. ventricular mass, wall thickening) characterizing cardiac cycle. Using such information we are able to calculate stroke volume, ejection fraction and cardiac output parameters.

3. VISUALIZATION METHODS OF THE LEFT VENTRICLE

The motion of the heart can be also characterized in terms of its local variations. It is possible to calculate displacement vectors: total displacement (relative to the reference frame T_0) and displacement between consequent time frames which can be seen as an instantaneous velocity. To be able to visualize the motion occurring on the surface (twisting) we can decompose the instantaneous velocity vectors into tangential and normal components. All of these local variations can be visualized in various ways. In our work we use two kinds of techniques - color and vector based. We can colorize the moving surface according to the

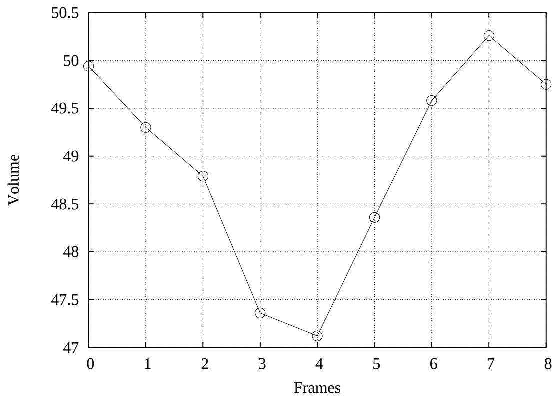


Fig.2. The plot representing volume changes of the left ventricle during reconstructed cardiac cycle.

length values of displacement vectors. It is strongly useful when dealing with small surface deformations. When the motion is significant it is better to visualize vector values using arrows representing length and spatial orientation of moving matter. The last method of motion visualization used in our developed system is called the *line-paths*. In this method we select the small set of surface points and visualize the path of their motion during the cardiac cycle using colorized polygons. Colours of the line segments represent consequent time frames. Such method enables to estimate the viability of the heart using a single image. In the addition to the line-paths method we may also generate so called *activity surface*. In this method we can visualize total path length values (in single cardiac cycle) for every surface point. Using this method on single static image we may estimate spatial extents of pathological regions. In this section we present results obtained using developed visualization methods. All of the images have been generated using 4D echocardiographic dataset (8 frames - $160 \times 144 \times 128$) of heart stroke patient. Using generated surface data we were able to calculate the volume changes during the cardiac cycle (see Figure 2). Figure 3 presents absolute displacement visualization of the motion frames from two different perspectives. Using this method it is possible to observe in details local variations of the ventricular surface between systolic (time frame T_4) and diastolic phases. For more detailed motion analysis we may use visualization of displacements relative to the previous time frames. This kind of displacement can be understood as instantaneous velocity. In this case we mainly deal with not significant surface deformations so vector visualization is not suitable. It is better to use colorized surfaces according to the length values of the displacement vectors. In the presented examples we colorized all images using greyscale lookup table where black colour represents zero deformation and white colour represents maximum deformation. From the physicians point of view it is very important to analyse normal and tangential motion separately. The motion in normal direction is responsible for volume changes of the ventricle while the tangential motion is highly connected with twisting of the heart muscle. Figure 4 presents visualization of the relative vector components for all of the time frames. It is clearly visible that in this case tangential component is dominating. The last two visualization methods: line-paths and activity surface present static visualization of the dynamic process (see Figure 5). Using this techniques it may be easily observed which regions are moving and how significantly during cardiac cycle. Line-paths visualization contains complete information about the motion but activity surfaces presents the overall surface activity more clearly.

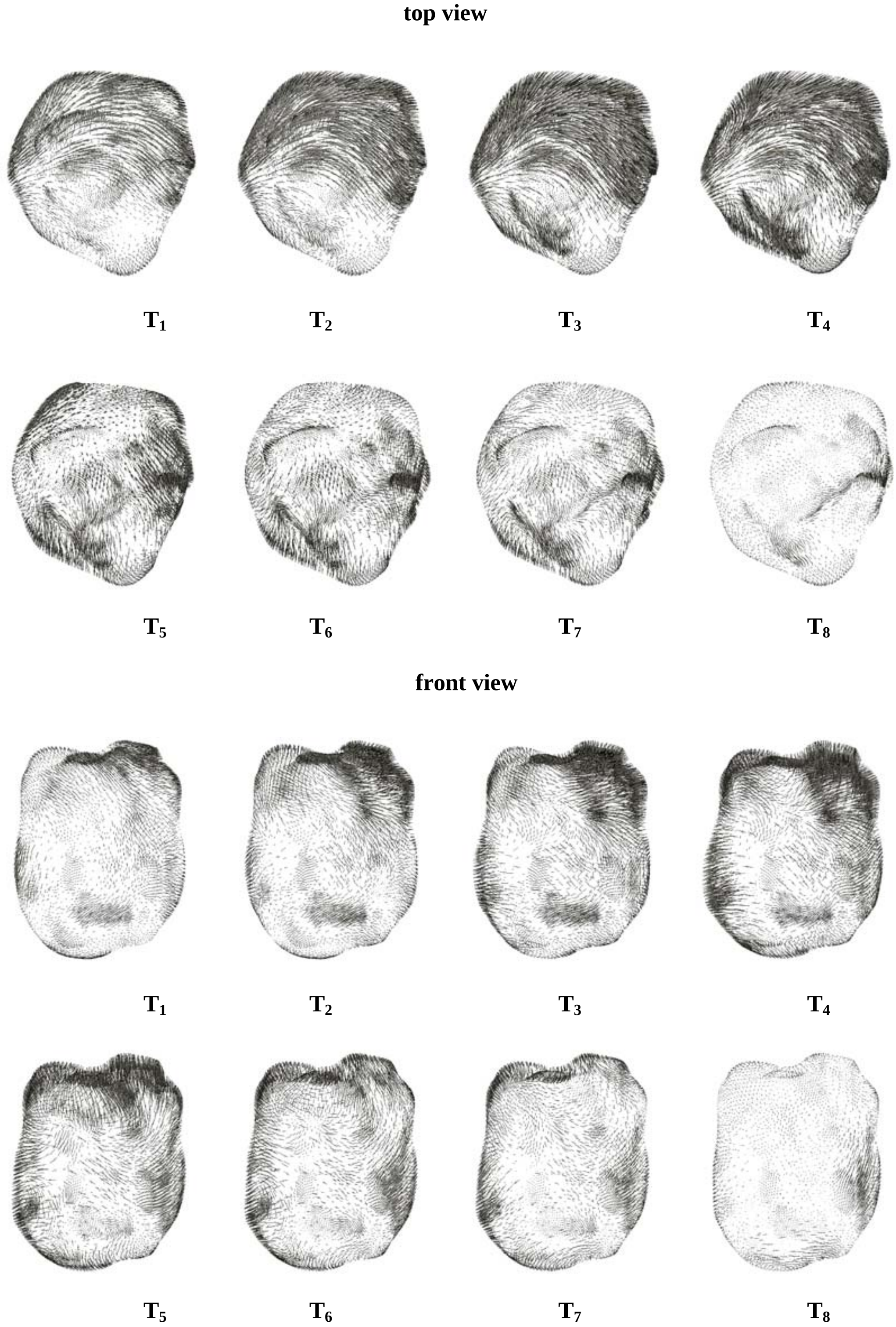


Fig.3. Absolute displacement vector visualization of cardiac cycle from two different perspectives.

4. CONCLUSIONS

In this paper we have presented a set of heart motion visualization methods based on 4D echocardiographic methods. We have shown the results obtained using clinical data set of a heart attack patient. In the physician's opinion, the proposed visualization methods enable to detect pathological regions of the beating heart with high precision and may be useful in daily clinical practice. In the near future we plan to work on the segmentation of the ventricular outer surface to enable more accurate description of the cardiac motion.

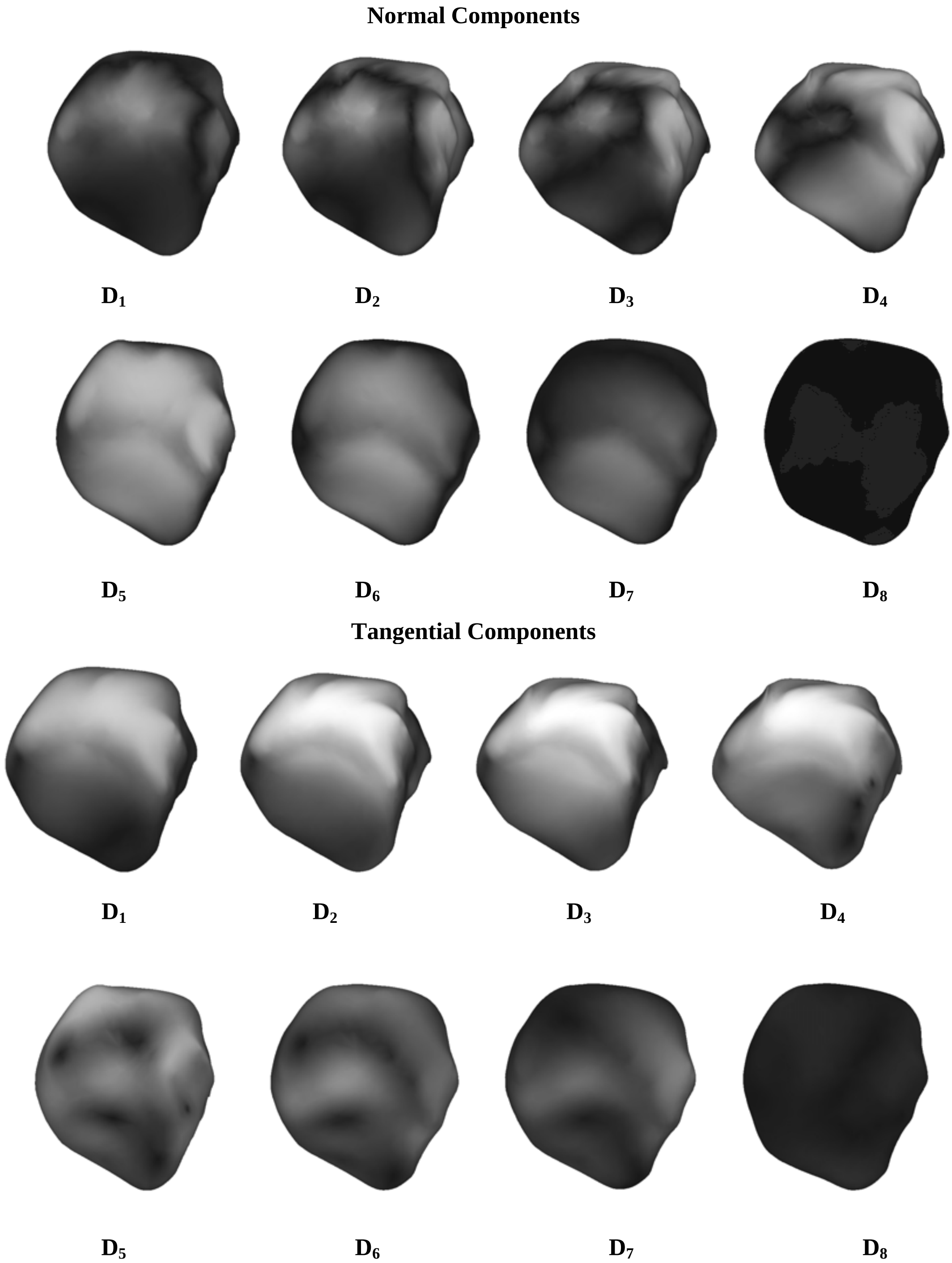
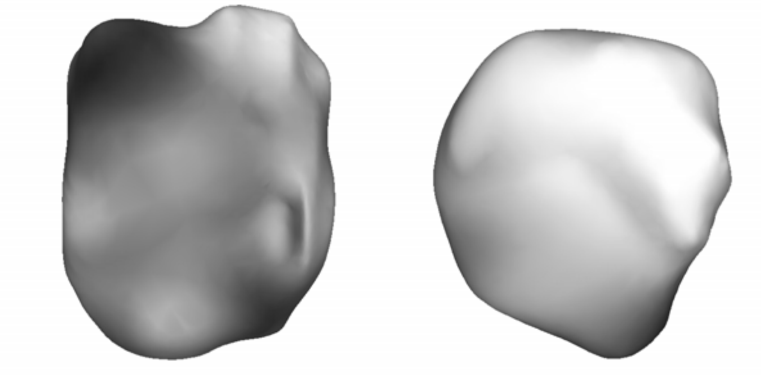


Fig.4. Normal and tangential components of instantaneous velocities (lengths of the vectors) visualized using colorized surfaces (max displacement - 12,71mm).

line-paths



activity surface

Fig.5. Line-paths and activity surface visualizations (max path length - 30.03mm) - front view (left column), top view (right column).

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