A MECHANICAL MODEL OF HEART VALVES WITH CHORDS FOR IN SILICO REAL TIME COMPUTATIONS AND CARDIOSURGERY PLANNING

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1. Introduction

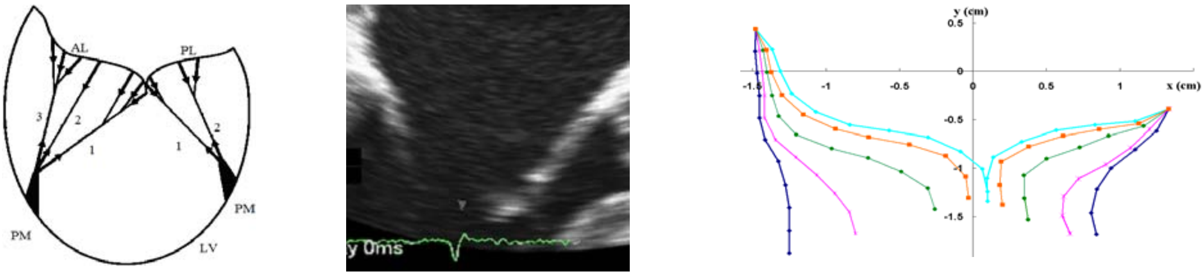
Development of mechanical models of biological tissues and numerical estimation of their strength and durability has become an important component of surgery planning based on individual geometry [1]. The models of the coronary stenosis, brain aneurisms, heart chambers have been used for clinical studies. Here a reasonable mechanical model of the mitral valve (MV) leaflets dynamically interacting with papillary muscles (PM in fig.1a) and a set of chords is proposed.

The MV is composed of two flexible leaflets from inextensible material (AL, PL in fig.1a) working to open during diastole and close in systole at the high blood pressure conditions [1]. The age-related and pathological changes of the leaflets can affect its mechanical integrity that may result in incomplete closure (MV regurgitation) which is the 2nd most common valvular problem in elderly in Europe. In the normal valve, the surfaces of leaflets have thin threads (chords) connecting them to the PM inside the left ventricle (LV in fig.1a) that prevents them from the movement inside the atrium during the systole. In the affected valves the chords are ruptured or over elongated that leads to the valve prolapse. Among the chords the primary (1), secondary (2) and tertiary (3) ones are distinguished depending on their location, thickness and number of branches (fig.1a).

Detailed 3d finite element models (FEM) have been recently developed on the individual geometries restored from CT images [2]. The visualization techniques of a beating heart are based on consequent imaging of the heart slices taken at the end of diastole when the heart is relaxed. Therefore, the obtained geometry is composed of the structures imaged at different beats when location of the heart may slightly differ due to breathing, spasms and other physiological fluctuations. Moreover, the FEM computations based on fluid-structure interaction formulations are time consuming and needed a special CFD team. In contrary, the model and approach stated below can be used for fast preliminary analysis and planning the surgery on restoration of the ruptured or over elongated chords followed then by corrected automatic computations by a surgeon when the heart is stopped and new details on geometry and biomechanics the structures become known.

2. Materials and methods

The dynamics of AL and PL of MF have been imaged (fig.1b) and digitized (fig.1c) from the ultrasound (US) records taken in healthy individuals and patients with different types of MV regurgitation. Both leaflets have been considered as k-link flexible threads which segments $k=1,2,\dots k_{AL}$ and $k=1,2,\dots k_{PL}$ possessed different Young modules $E_k \sim 10^5\text{-}10^6$Pa and flexural rigidity g_k. The values E_k correspond to rigid calcified, passive inextensible or active stretchable segments with muscle fibers incorporated. The values g_k describe the flexibility of AL and PL depending on their thickness, smooth/nonsmooth shape and affection by disease/degeneration. These values are known from review articles. Then the correct location of the edge of the prolapsed valve(s) has been introduced into the digitized dynamical data and the correspondent location and length of the corrected segment(s) have been computed basing on the E_k and g_k values of the corresponding segments. Then a typical geometry of the chords has been used as initial configuration.



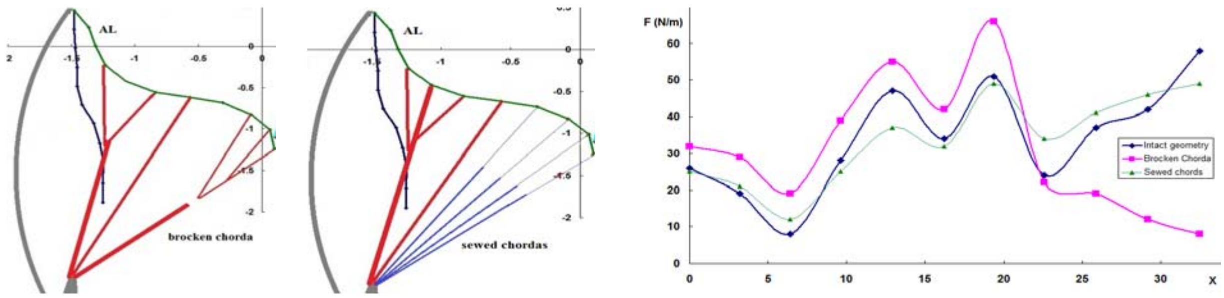
a b C

Figure 1. The structure of MV chords (a), US image (long axis view) (b) and digitized valve dynamics between t=0 s ad t=85 ms (c).

3. Problem formulation, results and discussion

The locations of the moving heart walls, papillary muscles and leaflets are defined by generalized coordinates $q_1(t),\ q_2(t),\ \ldots,\ q_n(t)$, where n is the number of DOF. The governing equations are 2-order Lagrange equations with generalized forces produced by action of the chordae $\hat{Q}_k = \hat{Q}_k\left(q_1, q_2, \ldots, q_n, \dot{q}_1, \dot{q}_2, \ldots, \dot{q}_n\right)$ and other generalized forces $\tilde{Q}_k$. The main forces produced at the leaflets by the stretched chords are $\vec{F}_i^{(s)}$. The chords are considered as nonlinear elastic springs which are no stretched when the valve is open. Then the general virtual work $\delta\hat{A}$ of all the forces on the virtual displacements $\delta\vec{r}_i^{(s)}$ and then the generalized forces can be computed from known values $\left\{\vec{r}_k(t), \dot{\vec{r}}_k(t)\right\}_{k=1}^{k_{AL}+k_{PL}}$ at different time instants.

The forces in the chords and leaflets have been computed from (1) at different locations of the sewed artificial chords instead of the ruptured one(s) (fig.2). Since for the artificial threads have $E\sim10^8$ Pa, the produced local stresses could damage the leaflets which happen in practice. The needed lengths and location of them could be efficiently estimated from the proposed approach.



a b c

Figure 2. A case study of brocken (a) and sewed (b) chordas and computed mean stresses along AL.

5. Conclusions

A very fast and efficient numerical approach for quantitative estimation of the heart valve surgery based on digitized US data is developed and proposed for clinical validation.

6. References

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