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Modeling Volume-Preserved Human Organs for Surgical Simulation

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Abstract

One of the challenging problems in surgical simulation is to reduce the computational cost to achieve interactive refresh rates for both haptic and visualization devices, while maintaining reasonable behavioural realism. Since human organs are predominantly based on water, they preserve overall volume during deformation. Therefore, representing the volume-preserved behaviour in dynamic system is essential to deliver realistic organ reaction in surgical simulation. Many existing methods for modeling and simulation of human organs often neglect the volume preservation due to its computational complexities. Otherwise, some previous volume preservation methods alter the material properties, resulting in hardened and unnatural dynamic behaviour. This paper presents a novel method to model human organs with volume preservation. It keeps the material properties intact and requires virtually no additional computation cost to address both computational efficiency and visual realism. Our method incorporates an implicit volume constraint on a simple mass-spring system. Experiments show that the object level volume is well maintained even under high pressure. Proposed method makes a realistic human organ simulation possible at an interactive rate with almost no additional computational cost.

Categories and Subject Descriptors (according to ACM CCS) I.3.5 [Computer Graphics]: Computational Geometry and Object Modeling

1. Introduction

With the recent advances in computer graphics and haptics, a multi-sensory direct interaction with 3D volumetric structures is becoming a viable future tool for medicine. Surgical simulation in virtual environments has been extensively studied to help medical students and surgeons to practice surgical skills [Bro96, CGC*02, CDC*96, PW89], and to plan and rehearse surgical operations [KGC*96]. It is well known that one of the most pressing issues in surgical simulation is to model and simulate the dynamic deformation of human organs realistic and efficient enough. The difficulties of modeling human organs for surgical simulations come from the fact that it involves highly complex material properties to simulate, yet the refresh rate should be at least 30 frames per second for visualization and 500 Hz for haptic device. Thus the effort of most researchers in modeling of human organs has been to find a reasonable solution and to take trade-offs between real-time interactivity and realism. One of the common physical behaviours of human organ is that it preserves overall volume during deformation. Volume penalty methods in nonlinear Finite Element Method (FEM) can be used to model the phenomena, but due to its heavy computational cost it is inappropriate for an interactive simulation. Mass-spring system is a widely used dynamic method, but conventional mass-spring system is based on the compression and elongation of springs, so it does not provide volume preservation property. This paper presents a modeling method for volume preserved human organs using a mass-spring system. Although there are many existing methods for volume preservation, the proposed method puts emphasis on the balance between interactivity and realism to make the system practical for many real-time applications. The complexity of the proposed volume preservation algorithm is constant time and requires virtually no additional computational burden.

2. Related works

Simulation of soft objects has been investigated from the perspective of computer-aided surgery, character animation, and biomechanics in the medical and the computation societies. In biomechanics, there has been considerable research on elastic properties of human-body tissue. Based on these experiments, many computational models have been proposed. Finite Element Methods (FEM) have been used exclusively for off-line simulations, but later several real-time approaches using pre-computation [JF03], modal analysis [CDA00, HSO03, JP02], and level of detail [CGC*02] have been reported. James and Pai [JP02] introduced the hardware acceleration of modal analysis based deformation and achieved the real-time refresh rate with a reasonably meshed structure. However it is based on pre-computed specific modes without considering all possible boundary conditions and it provides no solutions for topological change. Molino et al. [MBF04] introduced a method to change mesh topology during simulation but still the general computational cost is too expensive to provide interactive refresh rates.

3D ChainMail algorithm [Gib97] has been used for eye surgery [SBMH94] and knee surgery simulation [GFG*98]. The major drawbacks of 3D ChainMail algorithm are the lack of dynamics and the dynamic collision handling. Hollow organs like stomach and intestines cannot be represented properly because local deformation can not be propagated properly. In addition it may involve a node ordering problem that could cause significant computational cost when it chooses elements to apply deformation.

Mass-spring system has been widely used to simulate 3D volume deformable objects. Nedel and Thalmann [NT98] simulated a muscle with additional angular springs to preserve muscle shape, but their method uses an overly approximated volume calculation and volume preservation. Bourguignon and Cani [BC98] added artificial springs to the barycenter of tetrahedral elements. But their method can not guarantee the constant volume during deformation and adding stiff spring may cause numerical instability. Promayon et al. [PBP97] employed the Divergence Theorem to maintain constant volume using the projection method. However, it requires solving a third order equation to maintain the constraint volume. In addition, the projection method can reduce the numerical drifts, but may not guarantee the physically correct behavior similar to the post-stabilization method [CP03] because the constraint drift reduction operation is performed independently from the conforming dynamic motion of the object. Zordan et al. [ZCCD04] simulated the respiratory motion of a human body. They computed the total volume of object by summing up the pyramid elements (a surface triangle and the center of mass.

The element level of volume preservation maintains the overall volume of object by applying the constraints on every element. It is computationally very expensive and it can cause singularity on shared nodes when multiple constraints are trying to move the shared nodes to different directions to preserve the volume of each element.

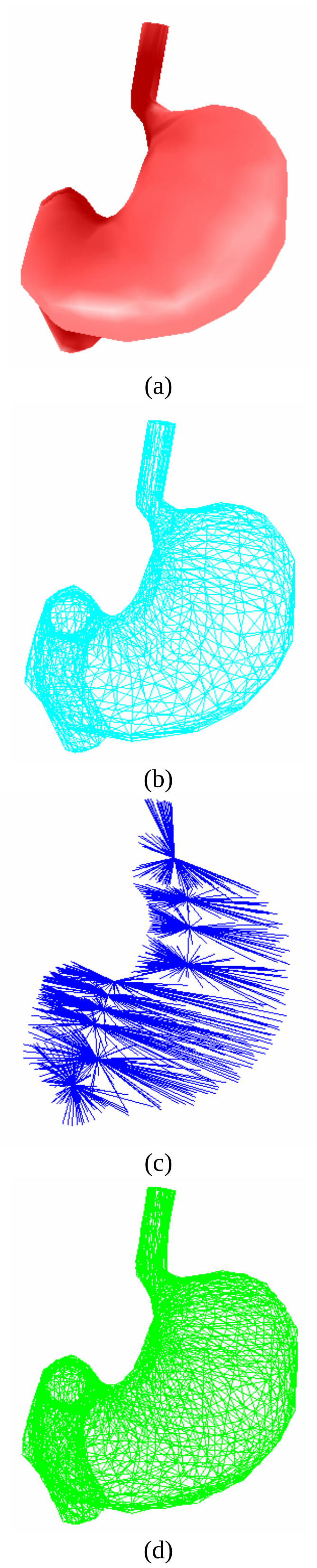
3. Modeling human organs

Human abdominal organs consist of complex and diverse types of tissues, and some organs are hollow. In addition, the detailed material properties of these soft objects are not well known yet. Since surgical simulation requires haptic devices to achieve the ergonomic feels of actual surgery, cheap computational cost at each frame is essential. Thus simple mass-spring system is often called for to achieve real-time interactive simulation. Biological soft tissues are almost incompressible compared to their low resistance to deformation. The stability and accuracy issues in numerical modeling of nearly incompressible materials by Finite Elements are now well understood, e.g. [JF03, CDA00, HSO03, JP02]. The central issue is that the accuracy of the incompressibility constraint must be carefully balanced with the accuracy of the approximation of the variables and computational cost. If the constraint is to be kept at a too accurate range, the mathematical model could become too stiff and may give completely wrong solutions unexpectedly, which is known as locking. If the constrain is too inaccurate, the overall accuracy becomes limited by the low accuracy of the constraint. Thus the ideal human organ model should consider these material, computational, and perceptual issues comprehensively to better fit the target application specific conditions.

To guarantee the sufficient refresh rate our human organ models are based on a mass-spring system. First the inner spring structure and dominant axis are computed according to the organ's topology. This inner structure provides a mechanism to propagate the locally applied force to the rest parts of an object. This scheme is a significant approximation of elaborate 3D volumetric meshing but it provides substantial performance advantages and particularly effective for maintaining the shape of hollow organs. Figure 1 (a) is a stomach model, and Figure 1 (e) is a liver model. Figure (b) and (f) show the main structural springs connecting direct neighbor nodes to model the elastic properties of the organ. Figure 1 (c) and (g) show the inner springs. To generate the inner springs, virtual nodes are added along the longest axis of the object. The inner springs are inserted between each node and its closest virtual node. The inner springs propagate the applied forces directly to the opposite sides of the object. Figure 1 (d) and (h) show the bending springs that represent flexural properties. The bending springs that connect the secondary neighbor nodes defines the bending and flexural properties of the material and it helps maintaining the rest-state shape of the object. The bending springs preserve the curvature of the surface.

4. Volume preservation

To overcome the critical inherent drawback of volume loss of a mass-spring system, this paper proposes a real-time volume preservation method. Our volume preservation method maintains the global volume of a closed mesh structure. The surface of a deformable object should be closed to provide the complete boundary of the object but there is no restriction on the convexity or topological configuration.



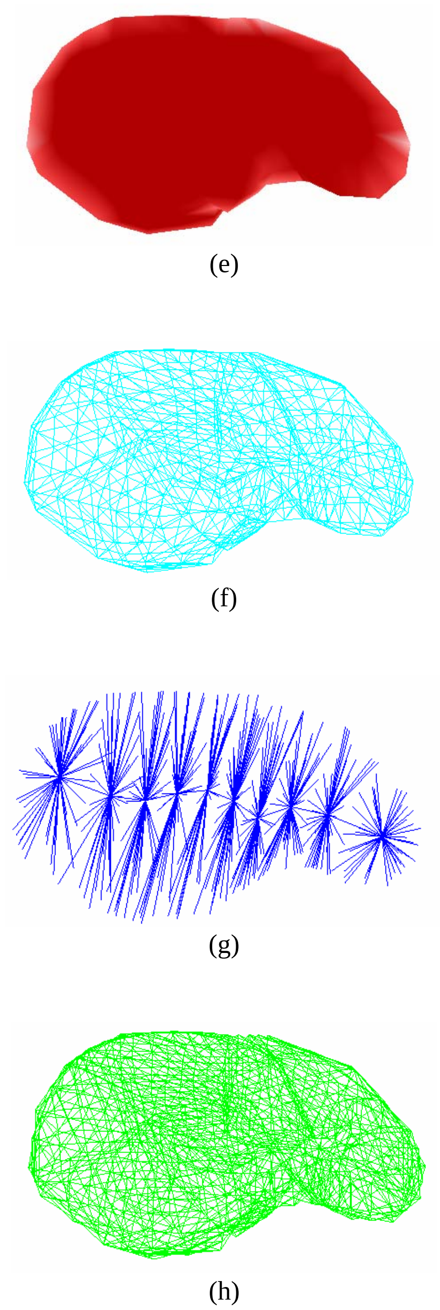


Figure 1: *The mesh structures of stomach and liver. (a) is a rendered stomach model, (b) shows structure springs of the stomach model, (c) shows inner springs of the stomach model, (d) shows bending springs of the stomach model, (e) is a rendered liver model, (f) shows structure springs of the liver model, (g) shows inner springs of the liver model, (h) shows bending springs of the liver model.*

The constraint equation for the volume preservation is driven using the Divergence Theorem to represent the relationship between a triple integral over the volume of a deformable object and a surface integral over the surface of object.

$$\iint F \cdot N \; dS = \iiint \mathrm{div}F \; dV \qquad (1)$$

F is a vector field of an object and N is a surface triangle unit normal vector. The total volume of a deformable object is estimated by summing the surface triangles of object. Assume that the vector F is the position vector r, thus $3\mathrm{V}=\iint \mathrm{r} \cdot N \; \mathrm{dS}$ can be computed by following equation (2). The surface is represented by flat triangular patches with coordinates (x, y, z) varying linearly on these patches. It is convenient to introduce the natural coordinates L_1, L_2, and L_3 and express the surface integral as

$$3\mathrm{V}=\int \sum_{i=1}^{3} \left(x_i L_i N_x + y_i L_i N_y + z_i L_i N_z \right) dA \qquad (2)$$

Note that the unit normal vector is constant on the triangular surface patch. The integral is easily evaluated using the following equation for integrating polynomials in L_i

$$\int L_1^{a_1} L_2^{a_2} L_3^{a_3} dxdy = 2A \frac{a_1!a_2!a_3!}{(a_1+a_2+a_3+2)!} \qquad (3)$$

where a_1, a_2, and a_3 are non-negative integers, and A is the area of a triangle. Since $a_1 = a_2 = a_3 = 0$,

$$\int L_1 dxdy = \int L_2 dxdy = \int L_3 dxdy = \frac{A}{3} \qquad (4)$$

The total volume V can be obtained by

$$V = \sum_i \frac{A_i}{3} \begin{Bmatrix} n_x(x_1+x_2+x_3) + n_y(y_1+y_2+y_3) + \\ n_z(z_1+z_2+z_3) \end{Bmatrix} \qquad (5)$$

where i is the volume contribution of surface triangle i. This volume must remain a constant over the entire simulation, so we cast this condition as a constraint in a dynamic system. The constraint-based formulation using Lagrange multipliers results in a mixed system of Ordinary Differential Equations (ODE) and algebraic expressions. We write this system of equations using $3n$ generalized coordinates, q, where n is the number of discrete masses, and the generalized coordinates are simply the Cartesian coordinates of the discrete masses.

$$q = \left[x_1 \; y_1 \; z_1 \; x_2 \; y_2 \; z_2 \; ... \; x_n \; y_n \; z_n \right]^T \qquad (6)$$

Let $\Phi(q,t)$ be the constraint vector made up of m components each representing an algebraic constraint. The constraint vector is represented mathematically as

$$\Phi\left(q,t\right) = \left[\Phi^1(q,t) \quad \Phi^2(q,t) \; .... \; \Phi^m(q,t) \right]^T \qquad (7)$$

where the Φ^i are the individual scalar algebraic constraint equations and m is the number of constraint. To preserve the volume of object, the difference between V_0 (original volume) and V (current volume) should be 0 during the simulation.

$$\Phi = V_0 - V = 0 \qquad (8)$$

We applied the implicit constraint method [HCJ*05] to maintain the volume constraint. Because of $m = 1$, the computation of unknown λ can be done with a simple division and no linear system needs to be solved.

5. Results

Our volume preservation method maintains the overall volume of the objects efficiently. An extreme example for volume loss was tested. Figure 2 illustrates the capability of our method to preserve the total volume and the behaviour of the object under the volume preservation constraints.

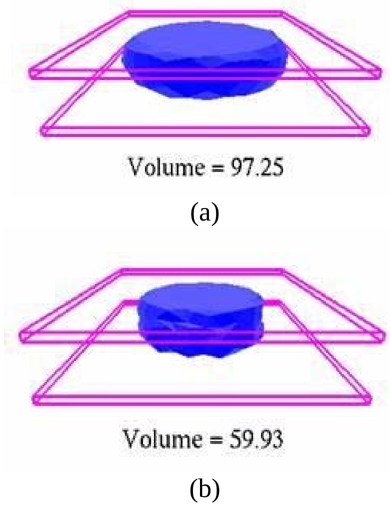


Figure 2: *The two planes squeeze the ball in the middle. After 800 iterations, the snapshot is captured. Our method (a) preserves the total volume, but the conventional mass-spring model (b) produces the significant loss of volume and distortion of the ball.*

Figure 3 displays the volume change of two methods throughout the simulation. We simulate stomach and liver to test our method. We applied the continuous point/triangle collision detection method utilizing Axis Aligned Bounding Box to reduce the collision query space. The stomach model has 1,096 triangles and 550 nodes. The liver model has 1,084 triangles and 550 nodes. Our method can maintain at least 40 frames per second in this simulation including rendering and collision handling on a 3 GHz Pentium 4 processor.

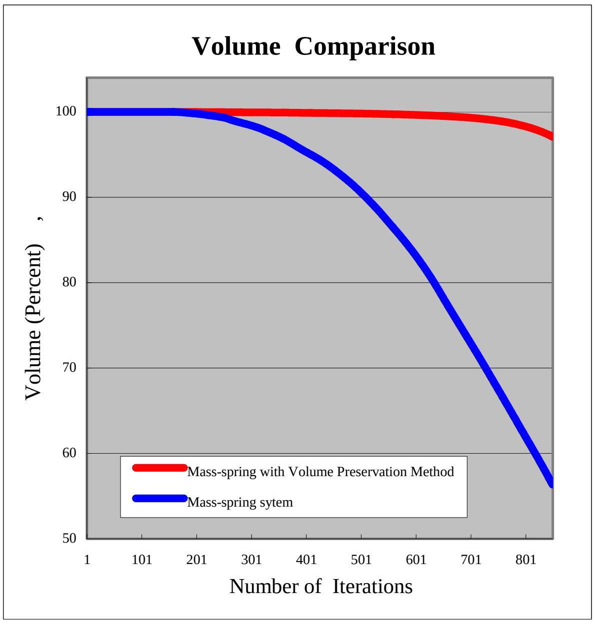
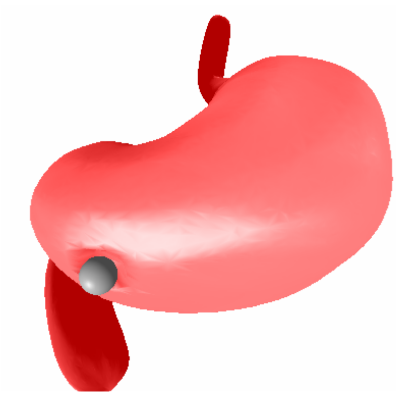
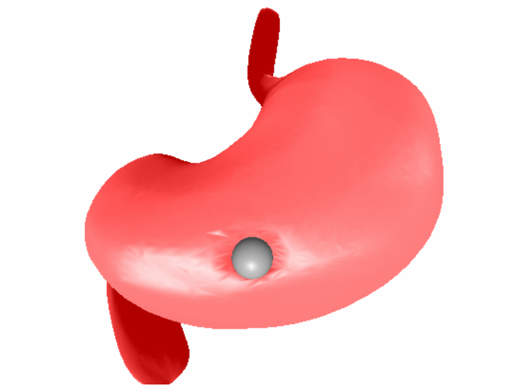


Figure 3: *The volume comparison chart between our proposed method and conventional mass-spring system.*

Figure 4 shows snapshots of the interaction between a refined stomach model and a surgical probe making a point contact. The stomach model includes over 19K nodes and 39K triangles. Currently the volume is preserved at an object level, so the effect is spread over the relatively large portion of its surface. The probe is entered to the lower left side of the stomach model and proceeds through the mid section to make a sliding contact shown in figure 4 (a) and (b). The tissue deforms locally around the contact area but its effect is propagated to the surrounding structure over time. During this prolonged sliding contact, volume preservation is well maintained and the frame rate is sustained at an interactive rate.



(a)



(b)

Figure 4: *The dynamic behaviour of the stomach under pressure (a) shows the initial contact with a surgical probe at the bottom of the stomach and (b) shows further deformation after prolonged pressure through the middle of the stomach.*

6. Conclusion

This paper presents a modeling scheme for human organs with a new volume preservation technique using an implicit constraint enforcement scheme. We take advantages of the simplicity and efficiency of a mass-spring system, but complemented it with adding volume preservation mechanism. The computational cost of the volume preservation is virtually negligible and the interactive level of refresh rate is guaranteed as long as the mesh density is within reasonable range. This enables us to achieve interactivity for surgical simulation using force feedback devices with added realism from the volume preserved human organs under pressure. Further studies on changing the topology of mesh structure would allow users to bisect the human organs and reflect the implicated volume changes.

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