Bender: An Open Source Software for Efficient Model Posing and Morphing

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Abstract. In this paper, we present Bender, an interactive and freely available software application for changing the pose of anatomical models that are represented as labeled, voxel-based volumes.
Voxelized anatomical models are used in numerous applications including the computation of specific absorption rates associated with cell phone transmission energies, radiation therapy, and electromagnetic dosimetry simulation. Other applications range from the study of ergonomics to the design of clothing. Typically, the anatomical pose of a voxelized model is limited by the imaging device used to acquire the source anatomical data; however, absorption of emitted energies and the fit of clothes will change based on anatomic pose.
Bender provides an intuitive, workflow-based user-interface to an extensible framework for changing the pose of anatomic models. Bender is implemented as a customized version of 3D Slicer, an image analysis and visualization framework that is widely used in the medical computing research community. The currently available repositioning methods in Bender are based on computer-graphics techniques for rigging, skinning, and resampling voxelized anatomical models. In this paper we present the software and compare two resampling methods: a novel extension to dual quaternions and finite element modeling (FEM) techniques. We show that FEM can be used to quickly and effectively resample repositioned anatomic models.

1 Introduction

The driving application for the work in this paper is the use of anatomical models in numerical simulations to characterize the absorption of radio frequency (RF) energy within tissues, and the associated temperature responses. The specific absorption rates throughout a body exposed to directed energies will change based on the body's anatomic pose. Acquiring anatomical body models in various postures and for various body types can be problematic due to medical scanner costs, post-processing labor efforts and acquisition constraints on pose. Typically, subjects must be lying down during x-ray computed tomography (CT) and magnetic resonance imaging (MRI) acquisitions, and therefore anatomical image datasets are mostly constrained to this pose. Repositioning systems that are tailored to a specific voxelized model do exist and provide accurate repositions of that single model [3,4]. These costly systems usually do not provide any method for repositioning other voxelized models. Researchers have also defined algorithms whereby precise anatomical mechanics can be derived from a voxelized model and used to reposition that model. These systems, however, require the specification of muscle and tendon connections and precise bone-joint modelling [5]. The level of detail required is beyond what is readily available and a significant operator time is required to define joint and muscle kinematics for these models as input to these algorithms [1,2]. Vaillant et al [14] developed geometric method that handles skin contact effects and muscular bulges in real-time. Kavan et al [15] have developed a skinning technique based on the concept of joint-based deformers. Mohr et al [16] presented a technique that uses examples that fit the parameters of a deformation model that best approximates the original data.

There is a need for open-source, freely available, and extensible software that can generate a new voxelized model that represents the original model resampled into the new position accurately and with only modest requirements regarding user effort and expertise. This paper introduces and evaluates such software.

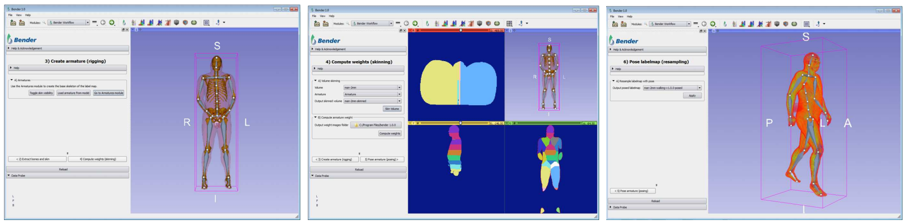
2 Methods

Bender is an open-source toolkit based on 3D Slicer [8] that provides algorithms and a user-friendly application for repositioning voxelized anatomical models into a desired pose [9]. It is a novel extension to computer graphics methods for rigging, skinning and posing to work with voxelized volumes [11]. The three main technical contributions presented in this paper are (1) the development of an easy-to-use workflow-based interface, (2) the incorporation of existing motion-capture database into the model-repositioning workflow, and (3) the development and evaluation of novel anatomical model resampling techniques.

2.1 Workflow

A workflow paradigm was chosen for Bender to provide an intuitive interface that guides users through the complexities of anatomic model repositioning. The steps of that workflow are as follows:

1. Rigging: This involves specifying a skeleton that represents the linear sections and joints of the body, by which the body will be repositioned (Fig. 1(a)). There are two options available to the user to define the rig: (1) they may click and drag in 2D or 3D views to place and edit each joint respectively or (2) they may modify by dragging the joints of an existing rig to fit the volume. Such task is relatively fast, especially with option (2); only a few minutes of work is required for this step.
2. Skinning: This is a 3D painting process in which the bones, soft tissues, and skin that should be moved with each rig section are explicitly associated



(a) (b) (c)

Fig. 1: (a) Rigging: Manually create or load an armature to fit on the volume bones. (b) Skinning: Associate a unique bone index for each anatomical voxel. (c) Posing: Reposition the anatomical model with a pose defined by the armature.

with each section (Fig. 1(b)). A default skinning map is generated by a heat diffusion algorithm on the rig using the underlying volume. Hinge joints, such as the elbow and knee, do not require much editing, however the ball and socket joints, i.e. the shoulder and hip joints, can be labor intensive. A few hours could be needed for this step. Note that the rigging and skinning are both one-time tasks for a given voxel volume.

3. Posing: The rigging is bent at its joints to define the target repositioning of the body.
4. Resampling: The bones, soft tissues, and skin in the voxelized model are resampled onto the repositioned rigging to create a new voxelized model (Fig. 1(c))

2.2 Incorporation of existing motion-capture data libraries

The posing task is achieved by the user clicking and dragging the rig to define joint rotations. Experience can be improved by adding rotation constraints at the joints. However, the posing step would still remain highly user-dependent. Specifying a pose that is mechanically feasible and that looks natural is a tedious task that requires extensive user interaction.

To simplify the posing process, we developed a pipeline to load predefined poses that are widely available over the web. Typically these offer outstanding realism because they

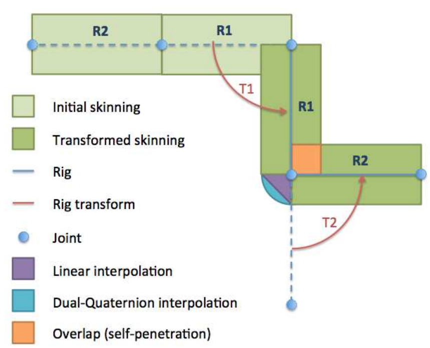


Fig. 2: Comparison between linear and dual quaternion interpolation techniques. While volume is more preserved in the elbow area with DQ interpolation, volume is lost in both cases in the forearm-arm junction due to lack of collision detection and force response

are created using human subjects and motion capture devices. The poses in these databases are typically specified using the Biovision hierarchy (BVH) file format [12]. This format defines a rig that represents the skeletal structure of the model and defines poses and sequences of poses as rotations at each joint in the rig. The Bender pipeline reads BVH files, fits the rig in the BVH file to the voxelized model, and skins the entire voxelized model (not only its surface) to that rigging. Defining a new pose that uses the same rigging is as simple as loading a new BVH file.

2.3 Advanced anatomical model resampling techniques

Bender incorporates advanced methods for resampling voxelized models, after rigging, skinning, and repositioning have been specified. The first resampling method is based on a linear resampling technique. For each voxel of the input models, the joints transforms (i.e. poses) are linearly combined using the weights derived from the skinning map. And each input voxel value is copied into the repositioned model at the voxel transformed coordinates. Linearly resampled models are typically not realistic as they do not take into account tissue deformation properties. The second resampling method is based on a Dual Quaternion technique for tissue deformation approximation [13]. Quaternion Spherical Linear Interpolation (Slerp) ensures constant-speed motion and improves the realism of the estimated deformation. This method is an improvement over the linear method; however, unrealistic tissue deformations can still result (see Fig. 2). To improve the resampling realism, particularly regarding self intersections, we implemented a Finite Element Method (FEM)-based resampling technique that takes into account tissue-specific deformation properties. FEM is a numerical technique for finding approximate solutions to boundary value problems for differential equations. Bender's FEM methods make use of the Simulation Open Framework Architecture (SOFA) [10] toolkit.

3 Experiments and Results

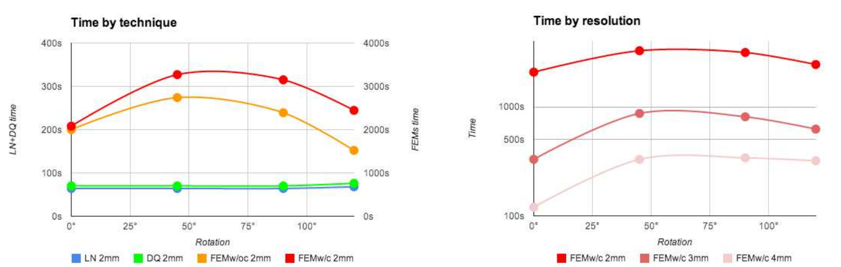
Experiments were conducted to evaluate the performance of Bender on arm repositioning. The experiments include quantitative and qualitative analysis to compare and contrast the different resampling techniques. The arm dataset was extracted from the Visible Man dataset and three subsampled volumes (2mm, 3mm and 4mm) were generated. The Bender workflow was then applied to each volume by following the same rigging and skinning steps. For the resampling step, we evaluated four techniques: linear interpolation(LN), dual quaternion interpolation (DQ), FEM without intersection (aka. collision) detection (FEMw/oC) and FEM with collision detection (FEMw/C). Four rotation angles were applied to the rig at the elbow joint ($0°$, $45°$, $60°$ and $90°$). For the FEM techniques, two extra steps were required: the voxelized model was tetrahedralized to generate a multi-material mesh and once that tetrahedral mesh was resampled, it was re-voxelized to obtain the final repositioned voxelized model. Three metrics were used to evaluate the techniques:

1. **Computational time** required to perform the repositioning.
2. **Volume preservation** of the total input volume was assessed. The metric can be obtained by calculating the ratio between the number of non-air voxels in the input dataset and the repositioned model. The ratio was also calculated for each individual tissue. A ratio of 0% signifies that there was no volume loss. A positive ratio means that volume was added through the repositioning process, and a negative ratio means that volume was lost.
3. A **qualitative study** was done to visually compare the results. We generated screenshots of the 3D rendered volumes for the general deformation and 2D reformatted slice views for the local changes and have subjects review and score the results.

Computational time: For all techniques, computational time is naturally proportional to the image size (Fig. 3(a)). Downsampling the dataset significantly reduces running time (Fig. 3(b)). The LN and DQ techniques behave differently than the FEM techniques regarding the rotation angles. Running time for LN&DQ techniques is relatively stable at any angle. For large rotations ($> 60°$), processing time is increased due to the number of voxels that must be filled by the interpolation techniques. Self-penetration does not impact the overall computation time as penetration is not detected by the LN&DQ techniques. For the FEM techniques, three trends can be observed. First, as the angle increases, computation time increases due to large deformations in the soft tissues; more steps are required to rotate the model. Second, as size of the image decreases, computation time is reduced. The voxelization of the posed tetrahedral mesh is performed by browsing through each voxel of the final image and calculating the label value of the voxel in the original input voxelized model. Lastly, the surface-based collision detection for the FEMw/C technique is computationally expensive. As a result, the FEM techniques are 20 to 30 times slower than the interpolation techniques. Experiments were run on a 2.33GHz 8-core 64b CPU desktop machine. All tested techniques are currently single threaded and do not use the GPU. We believe there will be a significant improvement in running the experiments on a multi-threaded implementation.

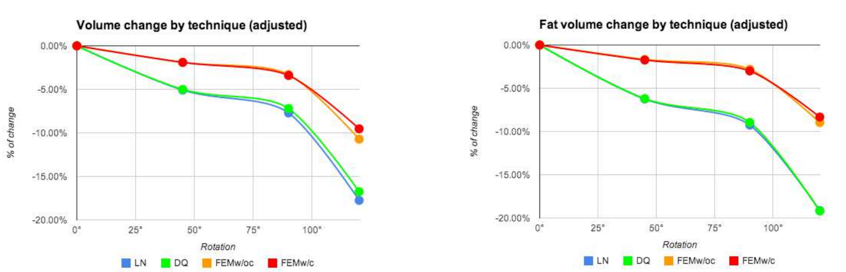
Volume preservation: The total volume and individual organ volume changes (e.g. fat volume change) follow the same trends (see Fig. 4). Generally, the FEM techniques preserve volume significantly better than the LN&DQ interpolation techniques. As expected, the Dual Quaternion technique has slightly better results than the linear technique. The FEM techniques with or without collisions produce similar results for small rotation angles, when there is no self-penetration. However the FEM with collision preserves volume better than the FEM without collision. Two limitations to this metric should be noted: firstly some living tissues can be heterogeneous and non perfectly incompressible and secondly the overall volume change may not accurately represent local changes. For example, for wide angles, volume is added by the DQ interpolation in the elbow region. However, volume is lost by the self-penetration. Further investigation of the FEM techniques will be needed in the future because volume is still being lost even when there is no self-penetration. This might be due to the FEM formulation.

Qualitative metric: The interpolation techniques and the FEM techniques results show significant difference in deformation (see Figures 5 and 6). However, within each category, only small differences can be noted. For example, except in the elbow area, the rest of the arm shows little difference for the LN and DQ techniques. Similarly, significant difference is observed in the elbow region for the FEM techniques. For the interpolation techniques, the DQ interpolation produces more realistic repositioned models in the elbow area than the linear interpolation. For the FEM techniques, the FEM with collision detection produces more realistic deformations even for small angles than the FEM without collision. Nonetheless, this comes at the expense of having to compute the self-collision interactions.



(a) (b)

Fig. 3: (a) Time by technique (b) Time by resolution



(a) (b)

Fig. 4: (a) Volume change by technique for all tissues and (b) for fat tissue only

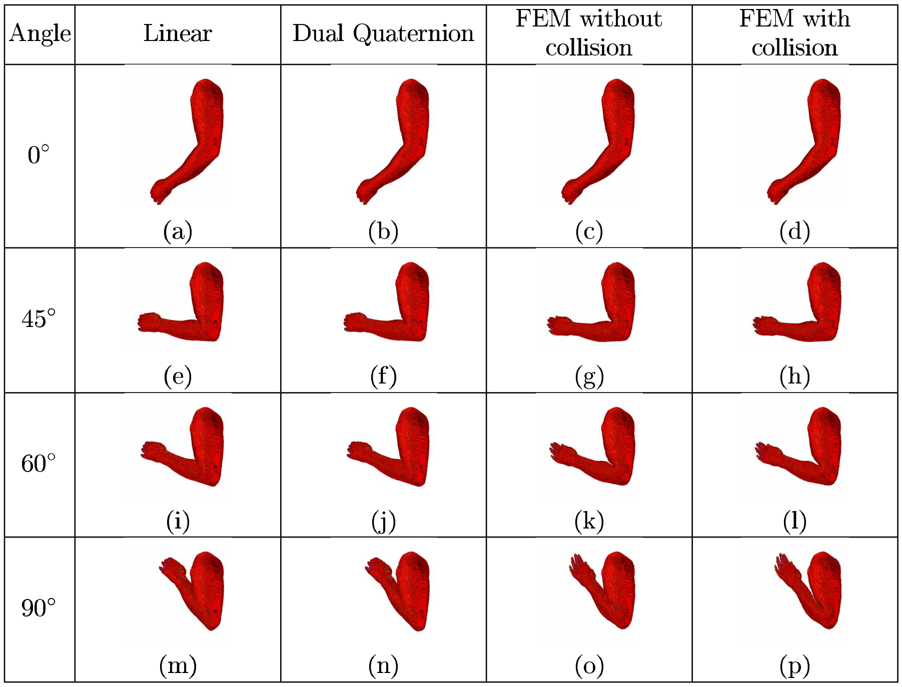


Fig. 5: 3D rendered visualizations of different arm repositioning techniques. The main difference resides in the anticubital area of the elbow.

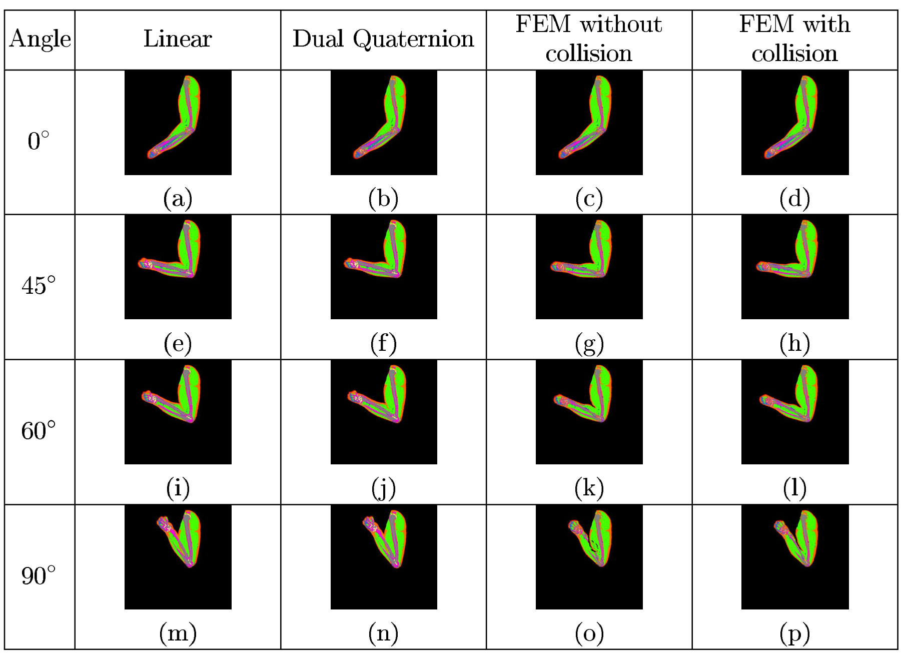


Fig. 6: 2D views of different arm repositioning techniques

4 Conclusion

We introduced, an interactive, software application for repositioning voxelized anatomical models. Bender is released as an open-source software that is cross-platform and freely available. The software provides a user-friendly workflow-based module for rigging, skinning and resampling voxelized anatomical models. Quaternion and finite element based techniques were developed and evaluated to resample the bones, soft tissues, and skin of the voxelized model onto the repositioned rigging. Future work includes improving the finite element formulation, the overall computational time and evaluation of results.

Acknowledgments. The development and evaluation of Bender has been supported, in part, by the AFRL SBIR FA8650-13-M-6444 and by the NIH grant R44OD018334.

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