A Dynamic-Image Framework for Geometric Modeling, Simulation and Analysis of Human Joints

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Abstract— We propose a dynamic-image driven, computational framework for the geometric modeling and simulation of multi-articular anatomical joints. The framework uses anatomic knowledge, computational methods, static and dynamic medical images to accurately measure bone kinematics and to model the subject-specific geometry of anatomical joints. The resulting models have application in biomechanical simulation, computer animation, and orthopaedic surgery. The first component of the framework is an automated tracking method for measuring with sub-millimeter accuracy multi-articular 3D motion. The automation of the method enables the study of subject-specific joint kinematics over large groups of population. The accuracy of the method enables the modeling and analysis of small anatomical features that are difficult to capture in-vivo using existing imaging techniques. The second component of the framework is a set of computational tools to model joint soft-tissue structures. We propose to build hybrid, dynamic-image driven geometric models that will combine the complementary strengths of the accurate but static models used in orthopaedics and the dynamic but low level-of-detail multibody simulations used in humanoid computer animation. Leveraging dynamic images and reconstructed motion, this component will allow the modeling and simulation of small anatomical features and of their dynamic behavior. The third and last component of the framework will enable the generation of predictive, subject-specific models and simulations of healthy and symptomatic joints. The predictive models will help to identify, understand and validate hypotheses about joint disorders.

Index Terms—Computational modeling, multibody simulation, visual analysis, dynamic medical imaging.

1 Introduction

Musculoskeletal disorders and diseases are the leading cause of physical disability in the United States of America [1]. Direct and indirect cost due to musculoskeletal conditions exceeds billions of dollars every year. As the average population age increases joint-related disorders will be more common because they are generally more prevalent in older people [1].

Despite the high socio-economic impact of musculoskeletal disorders, the underlying causes of many of these conditions and the effectiveness of different treatment methodologies are not well understood. An integrated framework for subject-specific modeling, dynamic simulation, visualization and analysis of anatomical joints can bring significant improvement in our understanding of joint motion dynamics and can help medical doctors for better diagnosis, treatment/surgery planning and recovery analysis of joint related diseases.

The goal of this interdisciplinary doctoral thesis is to design and implement a framework providing three functionalities: 1. subject-specific geometric modeling of joints based on captured medical images; 2. interactive visualization and dynamic simulation of the joints; and 3. defining and visually analyzing relevant anatomical measures for comparison and predictive purposes. Designing such a framework poses significant challenges from geometric modeling, visualization and overall interdisciplinary research perspectives.

Modeling of anatomical joints for dynamic simulation poses several significant geometric modeling challenges. First, what level of detail is necessary without significantly compromising the computational efficiency and the anatomical accuracy of the model? Second, modeling a complex system like an anatomical joint would require estimating many parameters, some of which may not be directly available. For example, geometric shape and mechanical properties of small anatomical structures such as ligaments and cartilage cannot be measured directly during motion due to technological limitations. As a result, to date, we do not have a subject-specific dynamic modeling and simulation technique for anatomical joints that would include skeletal soft-tissues such as ligaments and cartilage. Finally, challenges also lie in developing efficient and anatomically accurate soft-tissue deformation simulation techniques.

From a visualization perspective, this research presents several of the top scientific visualization challenges prepared by Chris Johnson [2]. First, the framework would require seamless integration of the visualization and interaction techniques with the modeling and simulation process to provide an integrated problem-solving environment. Second, as mentioned earlier, many parameters related to joint geometry and mechanics cannot be measured directly. Including the uncertainty about these parameters in the computational and visualization process is a significant challenge for this research. Recent advances in dynamic imaging technologies make possible to infer some of these parameters from dynamic motion information. The final challenge is proposing relevant anatomical measures to enable visual comparison.

We propose a dynamic-image based framework for subject-specific dynamic modeling and simulation of anatomical joints. We propose to develop computational tools to extract joint modeling parameters from captured static and dynamic medical images. The framework will be implemented as a collection of computational modeling and simulation tools augmented with interactive visualization and quantitative analysis capabilities.

2 Background

Joint Anatomy. The basic joint structure comprises several layers: 1. skin and fat 2. neurovascular system 3. muscles and 4. skeletal system. For understanding joint dynamics, modeling and simulation of muscles and skeletal structures is often sufficient since the other outer layers have no direct impact in joint functionalities and stability. Muscle fibers are connected with bones through tendons and apply forces on bones through contraction and extension.

Joint skeletal structures include ligaments, cartilage and bones. Ligaments are passive bands of soft-tissue structures which tether bones together, restrict joint motion and stabilize the joint. Articular cartilage acts as a cushion and shock absorber between joint bones. Progressive degeneration of the cartilage tissues cause osteoarthritis which results in significant pain, loss of motion and the functional disability of the

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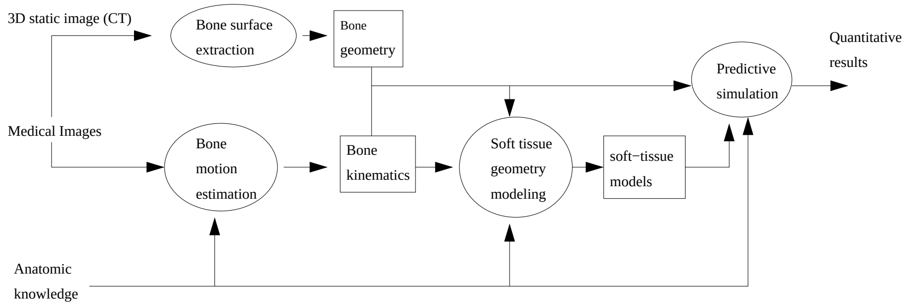


Fig. 1. Our proposed dynamic-image based framework for subject-specific modeling of anatomical joints. First, we estimate bone motion from captured dynamic images. Next, we infer the soft tissue geometry from bone models, motion information and anatomic knowledge. Finally, the framework allows predictive simulation using the developed model.

affected joint. The geometric and material properties of ligaments and cartilage tissues vary between joints and individuals. Accurate measurement of these parameters without invasive dissection of the articulation is not possible; this makes subject-specific modeling of these skeletal soft-tissues an extremely challenging problem.

Bones provide shape and load bearing capabilities to the articulations. The hard outer layer of bones is made of compact tissues. Inside the bones are spongy soft-tissues (trabecular). Due to hard outer layers, bones are represented as rigid bodies in articulation modeling and simulation.

Related Work. Existing computer aided joint modeling and simulation approaches can be classified in two categories based on model representation techniques: 1. finite element method and 2. multibody system approach.

The finite element (FE) method allows creating highly detailed models [3–5] by dividing a complex structure into many small elements. The FEM is mostly used for static and quasi-static simulations. The FEM is not well suited for dynamic modeling of articulations due to several reasons. Model development and simulation using FE methods is extremely time consuming and computationally expensive. In addition, FE models have limited capabilities to model the soft-tissue deformation that happens during dynamic simulation.

In the multibody system approach, joint components have much simpler representations such as a bone as a single rigid-body and a ligament as a single elastic fiber. Multibody system models have been used extensively by researchers for analyzing joint mechanics and predicting consequences of surgical procedures [6, 7]. However, since 3D soft-tissue structures cannot be captured directly during motion, the lack of geometric details in representing these tissues is a major limitation for multibody system models.

The FEM and the multibody system approach are at the two ends of the modeling spectrum; the FEM is highly detailed but computationally expensive whereas the multibody system approach allows efficient building and simulation of joint models but the model components lack anatomical details. An intermediate approach for subject-specific geometric modeling and simulation with relevant anatomical details is thus still missing in the literature.

3 Methodology and Plan of Research

The goal of this interdisciplinary research is building a framework for subject-specific dynamic modeling, simulation and analysis of anatomical joints. We plan to implement the framework as a collection computational geometric modeling and simulation tools integrated with interactive visualization and analysis techniques.

The success of our framework depends on how the framework addresses the previously mentioned challenges. To address the level of detail challenge, our framework will model skeletal soft-tissues because they have a significant impact on joint dynamics. However, simplifying assumptions will be made to reduce the computational complexity while keeping relevant anatomical measures significant.

Modeling of the soft-tissue structures lead another significant challenge. Skeletal soft-tissue structures are extremely difficult to image during motion due to technological limitations. To date, therefore, there is no technique for the modeling and simulation of articulations with subject-specific dynamic skeletal-soft tissue structures. We propose to address this challenge by computationally inferring the geometrical and mechanical parameters of the skeletal soft-tissues from joint bone motion information and 3D bone geometry.

Our developed modeling and simulation tools will be integrated with necessary visualization and interaction techniques to provide an effective problem solving environment to the researchers. Uncertainty about the directly unobservable parameters will be addressed by applying appropriate probabilistic models. Appropriate visualizations of the computed uncertainty will be created for visual comparison. We hope our collaboration with orthopaedic surgeons and bioengineers will help us to define relevant anatomical measures to enable visual comparison.

Proposed Framework. In this thesis we aim to develop a framework integrating computational modeling, simulation and visualization techniques for subject-specific analysis of anatomical joints. The framework is based on medical images captured both dynamically and at static postures.

Figure 1 shows the three basic components of our framework: 1. motion estimation 2. soft-tissue modeling and 3. predictive simulation. The basic idea here is that the motion data extracted from dynamic images should help us to estimate unknown soft-tissue geometries and behavior. In this thesis, we use dynamic radiographs to capture the articulation during motion and CT images to capture the 3D structure of the bones.

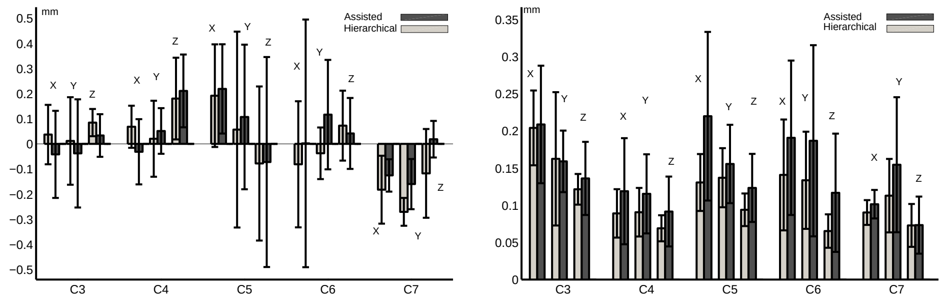
First, bone motion information is extracted from the dynamic x-ray images using our developed motion tracking tool designed for achieving high accuracy (sub-millimeter) and requiring minimum operator assistance. The accuracy of the method enables the modeling of small soft-tissue structures. Minimizing user interaction will enable large scale application of the tool and make the system operator independent. Next, we will use the bone motion information, 3D bone geometries and anatomic knowledge to compute the geometric models of skeletal soft-tissues such as ligaments and cartilage. Then, we will assemble the bone and soft-tissue models to generate the complete articulation model. Finally, the complete model will be used for predictive simulations.

4 Preliminary Work

Our proposed framework will be implemented as a collection of tools. The first component of our framework is a motion tracking tool. We have developed a motion tracking algorithm integrated with interactive visualization techniques for computing joint motion with submillimeter accuracy while keeping expert operator interaction to a minimum level.

4.1 Motion Tracking Algorithm

For motion tracking, we followed a model-based approach that matches dynamic radiograps (usually captured in a stereo-radiographic system) to a known bone shape. 3D models of the bones



(a) (b)

Fig. 2. (a) Bias and (b) precision of the hierarchical method and the assisted method. X, Y and Z denote the axes of comparison. The hierarchical method has achieved sub-millimeter accuracy for all vertebrae (C3-C7) and maintained similar precision as the assisted tracking method.

of interest are obtained using CT or MRI scans. Simulated x-rays are passed through the bone model to produce a pair of digitally reconstructed radiographs (DRRs) on the image plane. By calculating image similarity measures between the actual radiographic image pairs and the DRRs, the virtual bone position and orientation can be adjusted to identify the position that provides the greatest match, thus determining the position of the actual bone in space. This process is repeated for each pair of the images in the motion sequence, and repeated again for each bone of interest to yield the 3D position of the joint for the entire movement.

State of the art Operator-assisted Tracking. In conventional model-based tracking, the presence of overlapping bones (a common occurrence) reduces the quality of image matching and degrades tracking performance. Also, tracking each bone independently ignores the known characteristics of joints that constrain the relative bone movements. Significant expert-operator assistance is required for these methods to achieve the desired sub-millimeter accuracy for complex joints such as spine.

Proposed Hierarchical Tracking. We introduce a hierarchical multi-bone model approach, in which multiple bones are combined in a single 2D projection and simultaneously matched with the radiographs. This approach takes advantage of the rich detail present in regions of radiographic bone overlap, which can therefore enhance tracking performance. By incorporating hierarchical, anatomically aware, multi-articular models of joints, as well as temporal coherence, tracking reliability is further enhanced by exploiting known constraints that are defined across space and time.

Evaluation. 13 trials of cervical spine were acquired from 3 human subjects each with single-level anterior fusion. Tantalum beads were implanted into the cervical vertebrae so that a high accuracy ground truth solution could be produced by tracking the beads. The experimental results show that the hierarchical multi-bone method matches the sub-millimeter accuracy (Figure 2) of the state-of-the-art operator-assisted single-bone method. However, the hierarchical method is superior to the single-bone method in terms of robustness and run-time. For 5 of the 13 trials, the operator-assisted method failed to converge to a solution. Expert operators manually tracked the failed frames of those trials. On the other hand, hierarchical multi-bone tracking successfully finished tracking all frames of all trials. With the same hardware setup, the operator-assisted method required approximately 6 hours to track a single trial. The hierarchical method required approximately 0.5 hours, i.e., it attained a speedup factor of 12. These run times indicate the hierarchical method is cost-effective and operator-independent, which is essential for clinical application.

This work has been submitted to Med. Engg. & Phy. [8]. Validation of the hierarchical method on in-vitro lumbar spine data has been published at the ORS2012 [9].

4.2 Motion Tracking Tool Integrated with Interactive Visualization Techniques

Our motion tracking tool is integrated with interactive visualization techniques allowing users to be directly involved in the tracking process. Our interactive tool allows user to visualize the bone tracking and interact with the bone position and orientation if necessary.

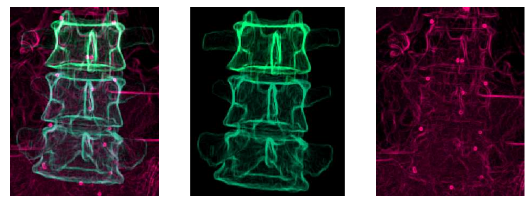
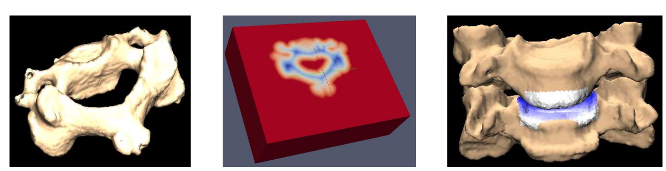


Fig. 3. Projection through multiple bones for hierarchical tracking. An overlay visualization (left), multibone DRR visualization (middle) and original x-ray visualization(right).

The tracking tool shows DRRs (produced by volume rendering) generated from multiple bones along with the real x-ray images (Figure 3). An overlay visualization helps the users to validate the quality of the matching between the projected DRRs and the real x-ray images. The user can select to show single or multiple bone projections to get a better idea about relative positioning of neighboring bones. A combination of select and zoom techniques further helps to look for details and validate the bone positioning. The operator can interactively change the bone position and orientation from global perspective or camera perspective, can choose to visualize original x-ray images or DRRs or their overlay display and can make an animation of the movement sequence to make sure that the bone motion is anatomically accurate.

5 Work In Progress

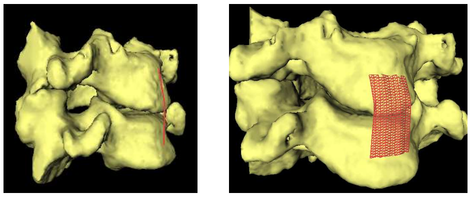
The second component of our framework is soft-tissue geometry modeling. As mentioned earlier, dynamic modeling of skeletal soft-tissues is the most challenging part in articulation modeling. We hypothesize that soft-tissue models can be inferred from the accurate motion information of joint bones, bone geometries and anatomic knowledge.



(a) (b) (c)

Fig. 4. Double representations of a bone model (a) mesh representation (b) distance field representation. Red indicates points outside the bone surface and blue indicates points inside the bone surface. (c) Inter-bone joint space visualization using the distance field information.

Ligament Modeling. 3D structures of ligaments are difficult to image during motion. Marai et. al. [10] developed a method for computing one dimensional ligament models from the bone geometry and motion information at multiple static postures. We plan to extend this approach to two-dimensional ligament representations using the motion information of a complete movement sequence.



(a) (b)

Fig. 5. (a) Path of a single ligament fiber and (b) a mesh generated from multiple ligament fibers.

In this thesis, we propose a dynamic-image based computational method for subject-specific modeling of articular ligaments. First, 3D images of the joint are captured using a CT scanner. Then a stereo x-ray setup is used to capture dynamic radiographs of the articulation during motion. Motion information of the joint bones is computed from the acquired images. To facilitate the faster computation of inter-bone joint space measurements, we use double representations (Figure 4) of the bone geometry. Ligament paths (5) during the complete movement sequence are computed using the double representations and the motion information of joint bones.

Finally, we hypothesize that the ligament paths and their variation during the motion sequence will provide insights into ligaments' geometric modeling parameters and mechanical properties. Currently we are at this final step of the ligament modeling process and we hope to finish the modeling process before the doctoral colloquium in October.

For ligament modeling, we assumed that ligaments are two dimensional surface to keep the modeling process efficient. Ligament insertion sites (where ligament fiber is attached with the bone) vary significantly from subject to subject and are very difficult to identify in-vivo. We will use a probabilistic model to address this issue.

6 Future Work

6.1 Cartilage Modeling

Similar to ligaments, capturing the 3D geometry of articular cartilage during motion is difficult using existing medical imaging technology. We hypothesize that the cartilage geometries at each point during motion can be approximated using accurate bone locations, 3D bone geometries and anatomic knowledge. Accurate bone locations can be estimated from 2D dynamic images captured during motion and 3D bone models.

We will integrate the cartilage modeling tool with interactive visualization techniques for effective modeling. We will design relevant anatomical measures to enable quantitative and visual comparison.

6.2 Predictive Simulation

There are two methods for anatomical joint simulations: 1. forward dynamics simulations and 2. inverse dynamics simulations. The forward dynamics simulation generates articulation motion from the forces acting on the joint. The inverse dynamics simulation computes the forces and torques on the joint bones from the captured motion data. We plan to perform inverse dynamic simulations because forward dynamics simulations require accurate models of all the joint components, their material properties and detailed external forces. Many of these parameters are unknown in practice.

We will assemble our developed soft-tissue models and bone models extracted from the static CT images to construct the articulation model. In our inverse dynamic simulations, we will analyze the impact of joint motion on the articular cartilage and ligaments. Both the cartilage and ligaments will be considered as elastic materials. For each pose across motion, we will track the cartilage contact area, compute the resulting stress and contact forces [10]. Ligament contact forces and moments both at the insertion and the wrapping sites will be computed.

7 Conclusion

In this doctoral thesis, we propose a dynamic-image driven framework for geometric modeling, simulation and quantitative and visual analysis of anatomical joints. We propose to extend the state of the art in joint modeling by including dynamic models of skeletal soft-tissues in the joint model while keeping the modeling and simulation process computationally efficient.

Our proposed framework will be implemented as a collection of modeling and simulation tools integrated with necessary interaction and visualization techniques allowing researchers to understand this challenging modeling and simulation problem interactively and more effectively.

Our preliminary results show that the bone motion information which is necessary for geometric modeling of joint soft-tissues can be computed efficiently and with the required accuracy using our developed motion tracking tool based on dynamic radiographs and static CT images of the joint bones. Furthermore, we have developed ligament path estimation technique using the bone motion information and bone geometry. Our current and future work includes completing the ligament modeling technique, geometric modeling of articular cartilage and developing inverse-dynamic simulation for the generated model.

Acknowledgments

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