Visualization of Contact Areas and Ligament Paths in Joints

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1 Introduction

We demonstrate a method for visualizing contact areas and ligament paths in articular joints. Contact areas define the cortical surface where bones articulate with each other. Visualization of contact areas and ligament paths has the potential to non-invasively highlight subtle but important differences between injured and uninjured joints. Animations of these visualizations are particularly helpful for understanding changes in relationships among bones.
We applied our technique to the distal radioulnar joint of a volunteer diagnosed with malunited distal radial fracture in one forearm. Our approach highlights modifications in injured forearm kinematics previously undetected.

2 Materials and Methods

Data Acquisition and Bone Modeling

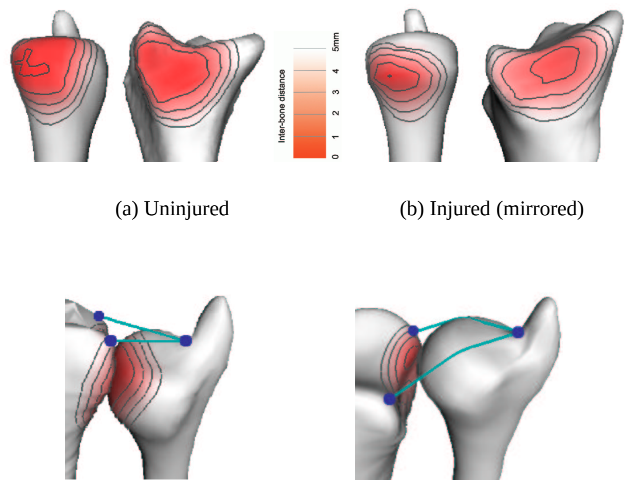
We capture 3D joint structures and kinematics using CT technology. 3D point clouds corresponding to the cortical surface of the bones are manually segmented from the CT images of the joint [1].
Bones are modeled both implicitly (scalar distance fields [3]) and parametrically (manifold surfaces [2]). We reconstruct a bone surface by fitting a manifold surface to the corresponding cloud of 3D points. Distance fields are computed using the reconstructed manifold bone model. A distance field is a scalar field which specifies the signed distance from a point to the bone surface. Sign is used to distinguish the inside from the outside of the bone.

Contact Area and Ligament Path Calculation

We compute a contact area as the surface on each bone where the inter-bone distance is less than a 5mm threshold. Using the distance field representation we find distances from every vertex in the surface model of each bone to every other neighboring bone. These distance values are updated for each frame of animation based on the joint kinematics. Iso-contours are computed on the contact area. Each contour shows where the distance map is equal to a constant distance.
We evaluate potential soft-tissue constraints in the joint by constructing minimum length paths between ligament insertion points. The anchor points are identified manually. The minimum paths are constrained to avoid bone penetration. These paths are generated via a sequential quadratic programming approach.

Visualization

We visualize bony contact areas using color mapping and contouring. We visualize ligament paths as polylines. Figure 1 demonstrates our technique. Color maps are generated for each bone so that distance values of surface points are mapped to varying saturations of color (red in the picture). The more intense the color, the closer two bones are. Contouring becomes very useful for grouping distances and, in this sense, complements the color mapping technique. Distances beyond a threshold value are neither colored nor contoured. They are shown as a white surface.



(a) Uninjured (b) Injured (mirrored)

(c) Uninjured (d) Injured

Figure 1: Contact areas (top) and ligament paths (bottom) in the uninjured and injured forearm of a single volunteer (both forearms in neutral position). Note the significant difference between the injured and uninjured joint: the contact area is significantly decreased and shifted downwards in the injured case. Note how the ligament paths wrap around the head of the ulna in the injured case.

3 Results and Conclusion

We present results from one application example: the comparison of normal and injured distal radioulnar joints (Fig. 1).
We introduce a 3D bone contact area and ligament path visualization method which can be used as a tool to explore hidden structures and subtle kinematics of joints non-invasively *in vivo*. The method presented has the potential to document changes in the joint mechanics that may influence long-term clinical outcome.
Preliminary results show that our method could be very useful in the study of both normal and pathological anatomy and kinematics of complex joints like the wrist. While the paths we generate are not actual ligament paths, they give a useful lower bound on the length of these ligaments. Thus, they help identify joint mobility constraints imposed by ligaments. Our technique may have applications to the study of wrist disorders such as rheumatoid arthritis, inter-carpal ligament tear - attenuation, and carpal-tunnel syndrome.

Acknowledgments

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References

[1] D. Moore et al., *3-D In Vivo Kinematics of the Distal Radioulnar Joint in Malunited Distal Radius Fractures*, Journal of Hand Surgery 27(2), pp. 233-242, 2002.

[2] C. Grimm et al., *Fitting locally parametric surfaces to 3D point clouds*, ASME Journal of Biomechanical Engineering, 124(1), pp. 136-140, 2002.

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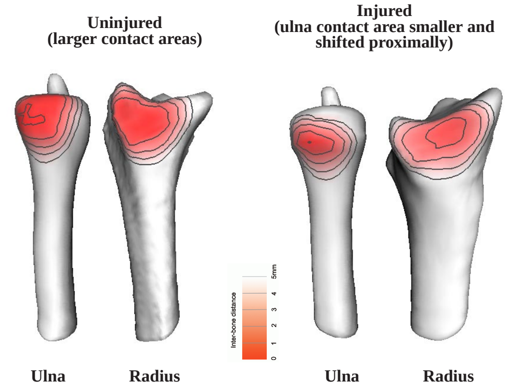
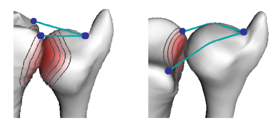
A. Summary

Visualization of bony contact areas and potential ligament path constraints can highlight subtle but important differences between injured and uninjured joints. We demonstrate a method for visualizing this type of information.

We applied our technique to the distal radioulnar joint. Our visualization captured modifications in injured forearm kinematics previously undetected. Doctors found our visualization technique particularly helpful for understanding changes in relationships between bones.



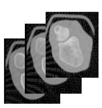


Uninjured (no ligament deflection)

Injured (ligament deflection)

B. Data Acquisition and Bone Segmentation

3D joint structure and kinematics are captured using CT technology. Points corresponding to the bone cortex are manually segmented from each CT slice and grouped to form a separate 3D point cloud for each bone. We recover bone kinematics via a surface distance minimization algorithm [1].

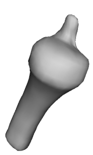


CT volume image

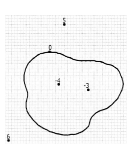
Segmented 3D point cloud (ulna)

C. Bone Modeling

Bones are modeled both implicitly (scalar distance fields) and parametrically (manifold surfaces). We reconstruct a bone surface by fitting a manifold surface to the corresponding cloud of 3D points [2]. Distance fields [3] are computed using the reconstructed manifold bone model. A distance field is a scalar field which specifies the signed distance from a point to the bone surface. Sign is used to distinguish the inside from the outside of the bone.

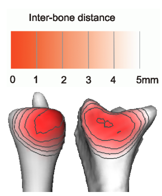


Manifold surface representation



Distance field representation (2D horizontal section)

D. Contact Area Calculation



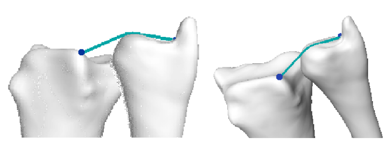
Contact areas define the cortical surface where bones articulate with each other. We compute a contact area as the surface on each bone where the inter-bone distance is less than a 5mm threshold.

Using the distance field representation of the bones we find distances from every vertex in the surface model of each bone to every other neighboring bone. We visualize contact areas using color mapping and iso-contouring [4].

E. Ligament Path Estimation

We model ligaments as minimum paths between anchor points. The minimum paths are constrained to avoid bone penetration. These paths are generated via a sequential quadratic programming approach.

While the paths we generate are not actual ligament paths, they give a useful lower bound on the length of these ligaments. Thus, they help identify potential joint mobility constraints imposed by ligaments.

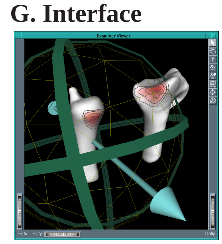


F. Visualization

Color maps are generated for each bone: distance values are mapped to varying saturations of color. Each contour shows where the distance map is equal to a constant distance. Ligament paths are shown as polylines.

In the pictures above, note the significant difference between the injured and uninjured joint: the ulna contact area is significantly decreased and shifted downwards in the injured case. Also, note how the ligament paths wrap around the head of the ulna in the injured case.

G. Interface



We have implemented a C++ and OpenInventor prototype of our visualization technique. The user can explode the joint for better viewing, disable or enable contour and distance viewing, and remove bones from the joint.

H. Conclusion

Our approach highlights subtle modifications, otherwise unnoted, in injured forearm kinematics. Statistics performed on a set of nine volunteers with the same disease correlate well quantitatively with the qualitative results shown here.

The method presented has the potential to document changes in the joint mechanics that may influence long-term clinical outcome. Preliminary results show that our method could be very useful in the study of normal and injured anatomy and kinematics of complex joints like the wrist or the knee.

Acknowledgments

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References

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