Validation of a Non-invasive Automated Hierarchical Method to Precisely Measure Lumbar Spine Movement

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Introduction:

An accurate, automatic and non-invasive motion tracking method is necessary to measure lumbar spine kinematics for clinical evaluation. Existing non-invasive dynamic 3D tracking methods are poorly suited for clinical applications. The state-of-the-art tracking processes [1-2] for determining 3D vertebrae kinematics from image sequences are highly labor intensive, requiring 10-30 hours of labor for every hour spent collecting data, dramatically increasing the cost for studies and making clinical applications impractical.

The purpose of this study was to validate an automated hierarchical tracking method that takes into account the complex structure of lumbar vertebrae and inter-vertebrae overlapping and tracks multiple vertebrae concurrently. This method was evaluated against an expert human operator-assisted model-based method that was previously the state-of-the-art. The major design objectives associated with the hierarchical method were to increase the robustness of the tracking process and therefore decrease the amount of time necessary to process data, while retaining high accuracy.

Methods:

Hierarchical Tracking: The hierarchical tracking method requires 3D bone models and dynamic x-ray images. 3D bone models were reconstructed from 3D volumetric images. We obtained 3D volumetric images of the bones of interest from a high resolution static CT scanner (LightSpeed 16, GE Medical Systems). A Dynamic Stereo X-ray (DSX) system was used to capture high resolution x-ray images [2]. DSX utilizes two frame-synchronized imaging systems each including a 100 kW high-frequency cardiac cine-radiographic generator (CPX-3100CV, EMD), a 0.3/0.6 mm focal spot size x-ray tube (G-1582; Varian), a 40 cm image intensifier (TH9447QX), and a high-speed camera providing 1800x2400 pixel resolution at up to 500 frames/sec with 14-bit dynamic range (Phantom V10; Vision Research).

For each x-ray frame in a motion sequence, a 2D projection (MDRR) is generated from the multiple reconstructed bone models. Next, both the x-ray and the MDRRs are processed to reduce noise and enhance edges. Finally, an optimization method searches through different positions and orientations of the bone models to find the best match between the MDRR and the x-ray image. The optimization method uses a hierarchical, muti-pass, coarse-to-fine search strategy to reduce the search space dimension (*6n* degrees of freedom for *n* bones) and to take advantage of temporal and spatial information while allowing sufficient degrees of freedom between bones to capture joint motion accurately. The process is repeated for all frames of a motion sequence**.**

Validation: To validate and evaluate our method, we performed a study on a cadaver of a 61 year old male (122 lbs, 18 BMI). The subject had tantalum beads inserted into vertebrae L3-L5. A total of 6 trials (flexion/extension, lateral bending, twisting) were captured and analyzed as part of this validation. Each trial was captured for 2 seconds at 60 fps. The maximum range of motion was approximately 190 mm translation and 60^0 rotations.

Implanted beads were tracked within the x-ray images to provide a "ground truth" solution for each trial. For both the operator-assisted and the hierarchical method, we quantified accuracy by calculating differences in bead locations in the ground truth and the respective tracking solution. Additionally, for each frame of every trial, relative translation and rotation between adjacent vertebrae were calculated (joint kinematics in anatomical coordinate system) from the bead-based, the operator-assisted model-based and the hierarchical method solutions to compare the operator-assisted and the hierarchical method against the bead-based ground truth.

In our study, the operator-assisted method was guided by an expert operator and solutions were checked and refined manually. The hierarchical method did not require any human assistance after initialization. We compared the solutions from these two methods in terms of accuracy, robustness and run time.

Results:

Accuracy: Implanted beads were tracked with precision of 0.11 mm, providing a highly accurate "ground truth" standard. Both the operator-

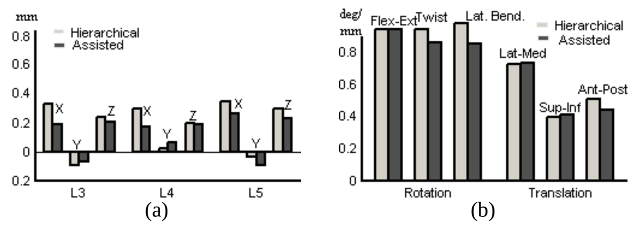

Fig. 1. (a) Precision (mm) of the hierarchical method and the operator-assisted method in lab coordinate system along X, Y and Z axes. Hierarchical method shows as good precision as the operator-assisted method. (b) Translation (millimeters) and rotation (degrees) accuracy of the hierarchical and the operator-assisted method when measuring joint kinematics. Results are summarized over 6 trials, 120 frames per trial.

assisted and the hierarchical method did not have any bias and were able to achieve expected sub-millimeter precision in all directions. Precision of the hierarchical and the operator-assisted method were 0.34 mm or better and 0.24 mm or better respectively (Fig. 1a). Precision in measuring 3D joint kinematics using the hierarchical method and the operator-assisted method were 0.98^0 or better and 0.94^0 or better in rotation respectively and 0.72 mm or better and 0.73 mm or better in translation respectively (Fig. 1b).

Robustness: The hierarchical approach was significantly more robust than the operator-assisted method. The hierarchical method did not require any operator assistance to keep vertebrae on track or any manual correction of the automatic solution. The operator-assisted method required on average 1100 manual interventions for each trial.

Run-time: The operator-assisted method required approximately 9 hours for each trial. 96% of the time was spent on human interactions. Using a similar hardware setup, the hierarchical method tracked a trial in approximately 1 hour. These run times indicate the hierarchical method is cost-effective, which is essential for clinical applications.

Discussion:

Our experimental results show that the hierarchical method matches the sub-millimeter accuracy of the state-of-the-art operator-assisted method on in vitro data. At the same time, the hierarchical method is superior to the operator-assisted method in terms of robustness and run-time. Notably, the hierarchical approach dramatically reduces the labor required for imaging studies, while making the accuracy and robustness of the method operator-independent.

However, the datasets we have used in our experiments were not from a heavy person (122 lbs). Future studies will analyze in vivo performance in the presence of higher noise due to soft tissue.

In conclusion, we have validated in vitro a hierarchical tracking method for measuring 3D lumbar vertebrae kinematics and compared its performance with the state-of-the-art model-based tracking method. A tracking method needs to be accurate, automatic and robust for large scale clinical use. The hierarchical method has shown good performance in these areas. In particular, the hierarchical method matches the accuracy of the expert operator-assisted method, while being operator-independent. The hierarchical method is more robust than the previous state-of-the-art model-based method. The method also reduces the total tracking time (9 times) significantly. The automation and the reduced run time will help to track a large number of trials and to understand human lumbar spine kinematics.

Significance:

An accurate, automated and non-invasive 3D motion tracking method will help to track a large number of trials and to understand human lumbar spine kinematics, lumbar spine related diseases and the effectiveness of different treatments.

Acknowledgment: This work was supported by NSF-IIS-0952720 and the Albert B. Ferguson Jr., MD, Orthopaedic Fund of The Pittsburgh Foundation.

References: 1. McDonald (2010) *Spine*. 2. Anderst (2009), *Med. Eng. Phys.*