ANALYZING THE PRECISION OF JSW MEASUREMENTS USING 3D SCANS AND STATISTICAL MODELS

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ABSTRACT

One of the methods to diagnose rheumatoid arthritis (RA) is measuring joint space narrowing over time. A method is presented to analyze the sensitivity of this measurement to positioning of the hand. Micro-CT scans are used to generate projections of a joint under varying angles of rotation. A semi-automatic method is used to measure the joint space width (JSW) for each projection. A Statistical model is used to investigate whether the rotation can be detected from a 2D radiograph. It is shown that rotation of the hand has a significant influence on the measured JSW.

1. INTRODUCTION

This paper describes a method to analyze x-ray images of the hand. This is done to assess the progression of rheumatoid arthritis (RA).

Currently, the diagnosis of RA is often done with the use of radiographs of the hands and feet. There are many different methods for scoring radiographs [1]. Most methods work by combining grades for bone erosion and joint space narrowing (JSN), the change in JSW over time. One drawback of the analysis with these methods is that the results are dependent on a subjective reader. This effect can be reduced by using a semi-automatic method [2]. Another drawback of the current diagnosis methods is that positioning of the hand can vary between exams. This leads to an unknown difference between measured JSW's. To determine this effect, we use micro-CT scans [3] to generate a series of projections with varying angles of rotation.

The micro-scans are used to generate a series of projections with only a difference in rotation. Of each projections, the JSW is measured using a semi-automatic method. This gives an indication of the sensitivity of JSW measurements to rotation. This sensitivity is then compared with the change of JSW over time, caused by RA.

A series of radiographs is then used to verify the results. A statistical model is used to determine a relation between the rotation and the shape of the bones of the radiograph.

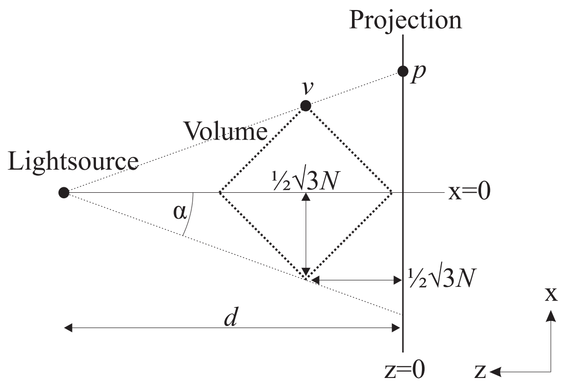

Figure 1: *Geometry used to generate projections of volume data*

2. VOLUME RENDERING

To analyze the effect of rotation of a hand to the measured JSW a series of projections is calculated from volume data. This section describes the projection method used. The projections are calculated to simulate the generation of a radiograph. Figure 1 gives an overview of the geometry used. The X-ray source is represented as a point source on the left. The rays from the source pass through the volume, and finally hit the 'projection' plane on the right of figure 1. The projection image is calculated by determining the intensity and position of the rays at the intersection with the projection plane.

To determine the effect of rotation, the coordinates of the volume are rotated as a first step in the projection algorithm. Projections of the volume are calculated using the 'splatting' method of Westover [4]. A cubic interpolation kernel is used, as it is shown to give sharper images than the gauss-function used by Westover [5]. The cubic kernel used here, the Catmull-rom kernel, is shown in equation 1.

$$h(t) = \begin{cases} 3/2|t|^3 - 5/2|t|^2 + 1 & |t| < 1 \\ -1/2|t|^3 + 5/2|t|^2 - 4|t| + 2 & 1 < |t| \leq 2 \\ 0 & otherwise \end{cases} \quad (1)$$

To calculate a projection, the position of the projection of each voxel on the image plane is calculated, using the geometry of figure 1. The volume data is assumed to be of size $N \times N \times N$. For each voxel v, the projection p at the plane $z = 0$ is calculated. To correctly perform the interpolation, the size of the projected voxel should be calculated. The size depends on the distance d of the lightsource to the projection plane and the distance v_z of the voxel to the projection plane. The size of the projection relative to the size of a voxel is given by $\frac{d}{d+v_z}$. If this scaling factor is larger than one, the extent of the interpolation kernel should be scaled by this factor. Otherwise, the amplitude of the interpolation kernel should be scaled with this factor. This is necessary to prevent aliasing errors.

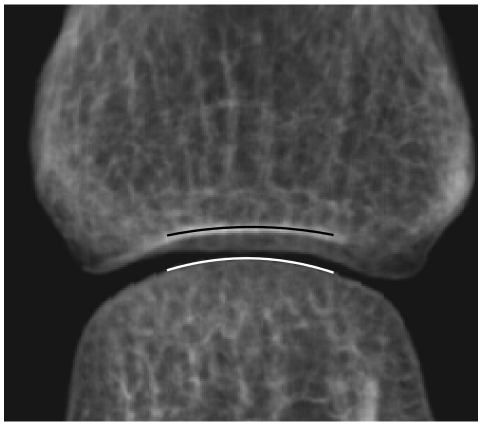

Figure 2: *Detected edges used for JSW measurement*

3. JSW MEASUREMENTS

Using the described projection method, a series of projections with very small differences in rotation of the volume can be generated. Since these differences are small, a precise method is needed to measure the JSW. To be able to compare the results, a semi-automatic method similar to the one presented by Sharp [2] is implemented. This method is shown to be fairly precise and to give results which are comparable to manual JSW measurements.

To detect the edges an optimization algorithm is used. As an initial estimate, four points on the edges are given manually. With this initialization two fourth order polynomial functions are calculated. Figure 2 shows an example for these two edges. For the upper edge, the optimization algorithm maximizes the intensity of the image under the polynomial function. For the lower edges the intensity of the vertical gradient of the image under the polynomial function is maximized.

To make the optimization more robust, the images are low-pass filtered to 1/20th of the original sampling rate. To further increase the robustness of the edge-detection the coefficients of the polynomial functions are not optimized directly: For each polynomial function, thirteen evenly spaced points are calculated. In one iteration of the optimization algorithm the vertical position of each of these points is optimized. After each point is optimized, the polynomial function is fitted to the points, and all points are recalculated using this function.

After the lines are fitted, the mean distance between the two lines is calculated. This is done by evaluating both polynomial functions at a large number of equidistant positions. For each point of one polynomial function, the closest point on the other is determined, and the distance between the two is calculated. The mean of the distances of all points is calculated and used as the JSW.

4. STATISTICAL MODELS

As will be shown in section 5, rotation of the hand does have an influence on the measured JSW. A statistical model is used to investigate whether the rotation can be determined from a radiograph.
The statistical model used is an active appearance model, which is fitted to an image using the inverse compositional algorithm [6]. The model is made by annotating a set of training images. Using the annotations the mean shape and the largest variations in shape of the bone can be calculated. This gives a shape model. By warping all images to the mean shape, a texture model can be generated. In the left of figure 7 the mean shape is plotted as a series of white dots on top of the mean texture.
The model is used by fitting it to radiographs. If this can be done precise enough, it may be possible to use the model parameters to determine the rotation of the hand from a 2D radiograph.

5. RESULTS

5.1. JSW measurements using volume data

Using the projection method of section 2 and the JSW measurement method of section 3 the effect of rotation of a hand on the measured JSW is investigated. The four volume datasets used to calculate the projections are acquired using a μCT-scanner and have been provided by J. Duryea [3]. These datasets have a resolution of 66 μm, which is similar to the resolution of a radiograph. For each dataset, the rotation is varied in steps of 1 degree. This is done for rotation around both the X-axis and the Y-axis of figure 5. In this figure the anterior-posterior view of an MCP-joint of a right index finger is shown. The X-axis is the horizontal axis, the Y-axis is the vertical axis. For each rotation, the projection of the volume data is calculated.

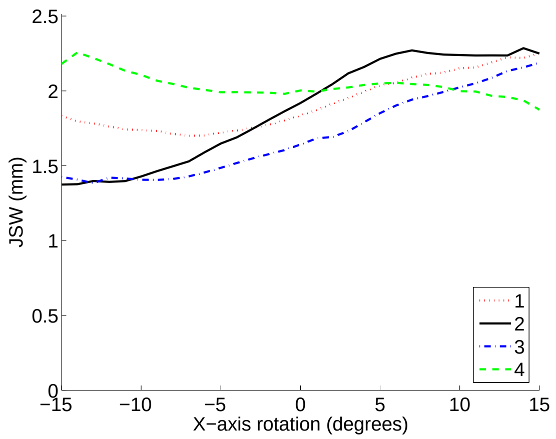

Figure 3: *JSW as function of rotation around the X-axis for four μ-CT scans*

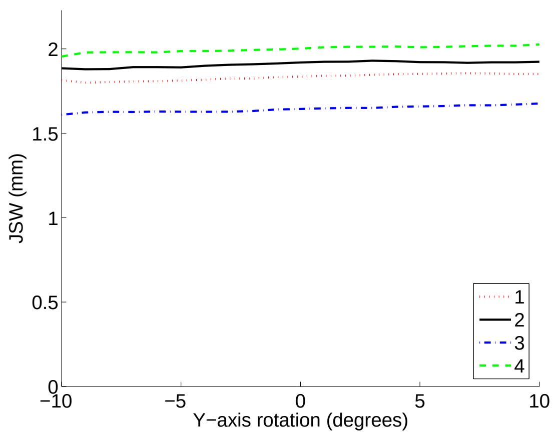

Figure 4: *JSW as function of rotation around the Y-axis for four μ-CT scans*

This is done using a parallel-ray projection ($d = \infty$ in figure 1). For the first image of a series of projections, the JSW measurement is initialized manually. Each following projection is initialized with the result from the previous one. Since there are only small differences between successive images, this gives a good initialization and the results are less sensitive to differences in initialization. The measured JSW's for each projection are plotted in figure 3 and 4.

As can be seen from these plots, the rotation of a hand around the X-axis has a noticeable influence on the measured JSW. Rotation of a hand around the Y-axis has a very small influence. Variations in the measured JSW are likely caused by the limited precision of the edge-detection algorithm. At a rotation of 0 degrees, the derivative of the curves of figure 3 are estimated by fitting a 3rd order polynomial function to the curves. The derivatives

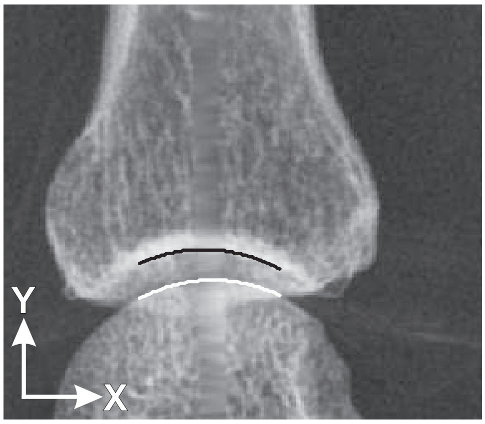

Figure 5: *Detected edges for JSW measurement of the skeleton*

range from 5 to 54 μm per degree rotation. To determine whether this change is significant, it should be compared to the change in JSW over time, caused by progression of the rheumatoid arthritis. Preliminary results from a study conducted for the 'Nederlandse Vereniging voor Reumatologie' show that the change in JSW is in the order of magnitude of 50 μm per year.

5.2. JSW measurements using a series of radiographs

To verify the results from the volume data, another test was performed. 6 radiographs of a hand skeleton were taken. The X-ray source was rotated in steps of 1 degree to generate six different images. Since the skeleton was held together by metal wires, image processing was used to remove the bright lines resulting from the metal. This was done by marking all pixels above a certain intensity as invalid. All invalid pixels were then interpolated from neighboring pixels using cubic interpolation.

Figure 5 shows the MCP joint of the index finger on one of these images. Along the vertical center of the bone, the image is vague, this is the result of the image processing. The two curves are the detected edges used for JSW measurement. By measuring the JSW for each of the images, the sensitivity of JSW measurements to rotation can be determined. For each radiograph, the JSW measurement is initialized manually. Results are shown in figure 6. The correlation between the rotation and the measured JSW is 0.82. The results are not as clear as the results generated using the volume data. Still, a strong relation between the rotation and the measured JSW is shown.

5.3. Statistical models

To investigate whether a change in rotation can be estimated from a 2D radiograph, a model of the proximal pha-

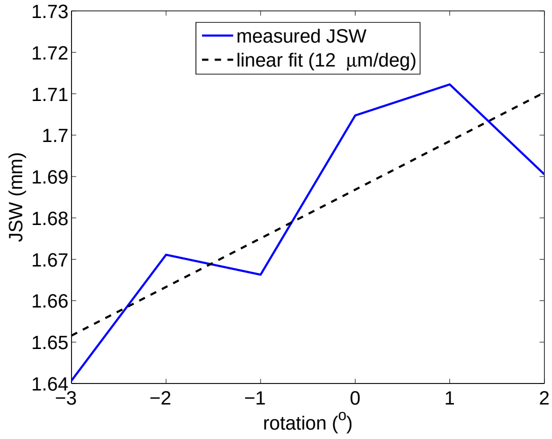

Figure 6: *JSW as function of rotation around the X-axis for a skeleton*

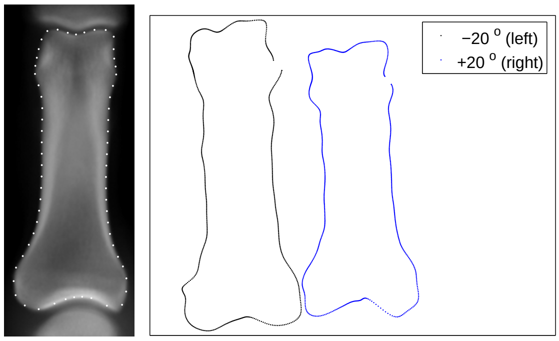

Figure 7: *AAM used to detect changes in rotation (left) and the estimated changes caused by rotation around the X-axis (right)*

lanx of the index finger is made. The left of figure 7 shows this model. This model is fitted to the six radiographs used in section 5.2. Although the fitting method was sensitive to initialization, the mean shape of the model could be used as initialization of the AAM. To test whether the AAM can be fitted precise enough, the correlation between the rotation and each shape parameter is calculated. 4 out of 14 shape parameters showed a correlation higher than 0.9.

To determine the effect of rotation on the image of a proximal phalanx, linear regression is performed on each of the shape parameters and the rotation. Using the linear relations between rotation and shape parameters, the shape can be estimated for arbitrary angles. At the right of figure 7 the shape is estimated for two large angles of rotation. This gives a visual impression on how the shape changes as a function of the projection angle.

6. CONCLUSIONS

Using four μ-CT scans and one series of radiographs, it is shown that a rotation of the hand or the X-ray source has a noticeable effect on the measured JSW. Although exact numbers are not known, for this case, the effect of rotating the hand by one degree is in the same order of magnitude as the change in JSW caused by progression of RA by one year.
An AAM was used to detect differences in radiographs caused by a rotation. Even though the method requires good initialization, AAM's can be fitted precisely enough to detect small changes caused by changes in rotation. Further research is needed, however, to determine whether a general relation between shape parameters and the rotation of a hand exists. It is therefore recommended to position a hand carefully and consistent before taking a radiograph. This is necessary to be able to use the JSW measurements as an indicator for the progression of rheumatoid arthritis.

7. ACKNOWLEDGEMENT

We would like to thank J. Duryea for providing the μ-CT scans of four MCP joints.

8. REFERENCES

[1] S. Boini and F. Guillemin, "Radiographic scoring methods as outcome measures in rheumatoid arthritis: properties and advantages," *Annals of the Rheumatic Diseases*, vol. 60, pp. 817–827, 2001.

[2] John T. Sharp, Jill C. Gardner, and Earl M. Bennett, "Computer-based methods for measuring joint space and estimating erosion volume in the finger and wrist joints of patients with rheumatoid arthritis," *Arthritis and Rheumatism*, vol. 43, pp. 1378–1386, June 2000.

[3] J. Duryea, J. T. Dobbins III, and J. A. Lynch, "Digital tomosynthesis of hand joints for arthritis assessment," *Medical Physics*, pp. 325–333, March 2003.

[4] Lee Westover, "Footprint evaluation for volume rendering," in *SIGGRAPH '90: Proceedings of the 17th annual conference on Computer graphics and interactive techniques*, New York, NY, USA, 1990, pp. 367–376, ACM Press.

[5] Stephen R. Marschner and Richard J. Lobb, "An evaluation of reconstruction filters for volume rendering," in *VIS '94: Proceedings of the conference on Visualization '94*, Los Alamitos, CA, USA, 1994, pp. 100–107, IEEE Computer Society Press.

[6] Iain Matthews and Simon Baker, "Active appearance models revisited," *International Journal of Computer Vision*, vol. 60, no. 2, pp. 135 – 164, November 2004, In Press.