Bone Alignment Using the Iterative Closest Point Algorithm

Maarten Beek, Carolyn F. Small, Randy E. Ellis, Richard W. Sellens, and David R. Pichora

Computer assisted surgical interventions and research in joint kinematics rely heavily on the accurate registration of three-dimensional bone surface models reconstructed from various imaging technologies. Anomalous results were seen in a kinematic study of carpal bones using a principal axes alignment approach for the registration. The study was repeated using an iterative closest point algorithm, which is more accurate, but also more demanding to apply. The principal axes method showed errors between 0.35 mm and 0.49 mm for the scaphoid, and between 0.40 mm and 1.22 mm for the pisiform. The iterative closest point method produced errors of less than 0.4 mm. These results show that while the principal axes method approached the accuracy of the iterative closest point algorithm in asymmetrical bones, there were more pronounced errors in bones with some symmetry. Principal axes registration for carpal bones should be avoided.

Keywords: modeling, kinematics, motion analysis

Modern imaging technologies provide detailed three-dimensional (3D) reconstructions of the surfaces of bones for surgical interventions and research in joint kinematics where it is essential to accurately register different models of a bone surface to one another to resolve changes in relative positions.

Many researchers have used the principal axes of the bones for establishing imbedded coordinate systems and determining their spatial orientations (Wolfe et al., 2000; Camacho et al., 2002; Ron et al., 2002) in part for ease of calculation. However, using principal axes to make kinematic measurements in carpal bones can be problematic due to their more symmetric shape. In a long bone like the radius an accurate estimate of the orientation of the first principal axis is possible even with noisy data. Even in the kidney bean shaped scaphoid the first principle axis may be accurately estimated because any rotation of that axis amplifies differences at the extreme ends of the bone. Rotations about that first principle axis show less sensitivity, thus the next axes are more difficult to estimate. In the relatively spherical pisiform, noisy data could result in an arbitrary orientation of the first principle axis, making it impossible to track its kinematics. In less noisy data, the orientation of the principle axes in the pisiform will still be uncertain due to its relative spherical symmetry.

Surface-based algorithms like the iterative closest point (ICP) algorithm, use all available surface information for registration (Besl & McKay, 1992). Although ICP requires additional computational resources and can be easily trapped in a local minimum without an accurate initial estimation, its accuracy is comparable to a fiducial gold standard if carefully applied (Neu et al., 2000; Herring et al., 1998). The more accurate volume-based registrations (Maintz & Viergever, 1998; West et al., 1999) are limited in application by their large computational requirements.

This paper reports results of tests on a subset of data from a kinematic study of four human cadaver forearms, conducted to verify the methodology. To eliminate segmentation bias, four carpal bones were dissected from one forearm and laser scanned. Using the resulting surface models as a reference, the accuracy of registration based on principal axes was compared with ICP. Principal axes alignment provided adequate initialization of ICP. In addition, the sensitivity of ICP to inter- and intraoperator variations in surface reconstruction was investigated.

Methods

Four fresh frozen human cadaver upper limbs (three different donors) were used, as approved by the Queen’s University and Kingston General Hospital Research
Ethics Board. Each ulna was rigidly mounted to an acrylic jig. Selective traction on nylon cables sutured to the tendons of the five main wrist muscles (flexor carpi radialis, flexor carpi ulnaris, extensor carpi radialis longus, extensor carpi radialis brevis, extensor carpi ulnaris) enabled the wrist joint to be positioned in twelve poses, beginning and ending with neutral. Computed Tomography (CT) scanning was performed using a LightSpeed Plus scanner (GE Medical Systems, Waukesha WI) at Kingston General Hospital. The in-plane resolution of the CT images was $0.235 \times 0.235 \text{ mm}^2$ and the interpolated distance between each image (slice thickness: 1.25 mm) was 0.625 mm.

After CT scanning, the scaphoid, lunate, triquetrum, and pisiform were dissected from one forearm specimen and scanned with a laser scanner (Applied Precision Inc., Mississauga, ON, Canada, rated accuracy 0.2 mm) as reference bones.

Mesher software developed at Queen’s University was used to segment the radius, ulna, and carpal bones from the CT images using a threshold value of 300 Hounsfield units, and to obtain 3D triangulated-mesh surface models of each bone through a marching cubes algorithm (Lorensen & Cline, 1987). Surface models typically contained 7,000 (pisiform) to 30,000 (capitate) vertices. The accuracy of reconstructions of carpal bones imaged in nonneutral positions was evaluated by comparing the surface meshes of the four reference bones in all twelve scans to the laser-scanned models. Most images were segmented by one operator; however, selected CT images were segmented by three different operators to determine interoperator variability.

C++ (Visual C++ 6.0, Microsoft Corp., Redmond WA) and VTK 4.2 (Kitware Inc., Clifton Park NY) libraries were applied to develop the software needed for the analyses. Surface areas were calculated by summation of the area of each triangle of the surface model. Volumes were calculated by summation of the (signed) volume of the prism under each triangle of the surface model. The areas and volumes generated by the same operator were averaged for each bone of each specimen. The principal axes were determined from the eigenvalue decomposition of the covariance matrix of the coordinates of the vertices of the surface models (Belsole et al., 1988). A graphical interface was developed to give the operator visual feedback on the orientation of the principal axes, and to occasionally correct the first and/or second principal axis by reversing them to match our sign convention for the orientation of the surface model.

Custom software was developed to align the carpal bone models from the ten non-neutral wrist poses with their neutral pose models using their principal axes (see above), after which ICP was applied. Convergence was considered complete when the inter-iteration change in the mean minimum distance between vertices of two surface models reached 0.001 mm. Alignment accuracy was evaluated by determining the mean shortest distance of all vertices of one surface model with their closest vertex on the other surface model and compared with values obtained from the principal axes alignment using a Mann-Whitney statistical test.

**Results**

**Intraoperator and Interoperator Variability in Reconstruction**

The maximum variability in surface area was 150 mm$^2$ for the capitate ($n = 12$). As intraoperator variability measures, the surface area and volume both had typical standard deviations of 4% of their mean values (Tables 1 and 2). Comparison of surface models of the reference bones generated by three different operators from the speci...
same CT images to quantify the interoperator variability, showed a standard deviation for the areas of less than 12% of mean values in all four bones, and of less than 5% (n = 3) for the volumes (Figure 1).

Reconstruction and Registration

As a segmentation accuracy measure, we compared CT surface models for the reference bones from the two neutral wrist poses with their laser scanned models. All scans and reconstructions were performed by the same operator and aligned using ICP. The mean shortest distance between any two of the models was less than 0.5 mm. The largest minimum distance between vertices was 2.47mm for the scaphoid.

After alignment using ICP, the mean minimum distance between surface models for all four bones was less than 0.4mm (Figure 2). Principal axis alignment showed a significantly higher mean minimum distance between CT models and the laser scanned model for all four bones, from 0.35mm to 0.49mm for the scaphoid and from 0.40mm to 1.22mm for the pisiform (p < .001). The mean angular difference between principal axis and ICP alignment was 10.6° for the pisiform (maximum: 25°) and 1.6° for the scaphoid (maximum: 3.7°). For a table with average carpal bone sizes to put our findings into perspective, the reader is referred to a recent study by Crisco and coworkers (Crisco et al., 2005).

Table 1  The mean (standard deviation) of the surface area of the reconstructions of the carpal bones in mm$^2$ for all four upper limb specimens, together with the average of these specimens. Each reconstruction was obtained from twelve sets of CT images that were segmented by one operator. The variation in the values found for the surface areas are indicative for the intraoperator variability in the segmentation of CT images.

<table>
<thead>
<tr>
<th>Bone</th>
<th>Arm41</th>
<th>Arm42</th>
<th>Arm43</th>
<th>Arm43b</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capitate</td>
<td>2101.88 (151.54)</td>
<td>1613.31 (59.80)</td>
<td>1363.32 (27.40)</td>
<td>1390.73 (65.91)</td>
<td>1617.31 (341.89)</td>
</tr>
<tr>
<td>Hamate</td>
<td>1699.33 (107.59)</td>
<td>1515.33 (37.61)</td>
<td>1209.04 (15.75)</td>
<td>1185.65 (45.54)</td>
<td>1402.34 (248.52)</td>
</tr>
<tr>
<td>Lunate</td>
<td>1237.09 (111.12)</td>
<td>1198.84 (42.31)</td>
<td>868.34 (23.09)</td>
<td>920.92 (24.60)</td>
<td>1056.30 (188.56)</td>
</tr>
<tr>
<td>Pisiform</td>
<td>590.40 (34.50)</td>
<td>516.40 (8.15)</td>
<td>502.12 (6.73)</td>
<td>539.46 (19.89)</td>
<td>537.09 (38.72)</td>
</tr>
<tr>
<td>Scaphoid</td>
<td>1587.68 (94.25)</td>
<td>1483.80 (45.67)</td>
<td>1111.66 (33.60)</td>
<td>1210.96 (47.96)</td>
<td>1348.53 (224.00)</td>
</tr>
<tr>
<td>Trapezium</td>
<td>1462.67 (115.31)</td>
<td>1307.85 (62.85)</td>
<td>1602.47 (46.36)</td>
<td>1236.35 (128.23)</td>
<td>1402.34 (163.47)</td>
</tr>
<tr>
<td>Trapezoid</td>
<td>1062.99 (71.56)</td>
<td>810.72 (55.98)</td>
<td>740.52 (35.91)</td>
<td>719.62 (49.23)</td>
<td>833.46 (157.90)</td>
</tr>
<tr>
<td>Triquetrum</td>
<td>965.55 (67.89)</td>
<td>886.99 (28.90)</td>
<td>837.33 (15.71)</td>
<td>954.19 (23.14)</td>
<td>911.02 (60.12)</td>
</tr>
</tbody>
</table>

Table 2  The mean (standard deviation) of the volume of the reconstructions of the carpal bones in mm$^3$ for all four upper limb specimens, together with the average of these specimens. Each reconstruction was obtained from twelve sets of CT images that were segmented by one operator. The variation in the values found for the surface areas are indicative for the intraoperator variability in the segmentation of CT images.

<table>
<thead>
<tr>
<th>Bone</th>
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<th>Arm43</th>
<th>Arm43b</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capitate</td>
<td>4201.34 (251.00)</td>
<td>2752.50 (166.11)</td>
<td>2724.69 (43.79)</td>
<td>2580.03 (101.06)</td>
<td>3064.64 (761.56)</td>
</tr>
<tr>
<td>Hamate</td>
<td>2925.60 (228.90)</td>
<td>2386.64 (146.86)</td>
<td>2106.92 (45.67)</td>
<td>1906.49 (68.03)</td>
<td>2331.41 (442.36)</td>
</tr>
<tr>
<td>Lunate</td>
<td>1988.96 (178.54)</td>
<td>1685.28 (129.52)</td>
<td>1539.47 (40.91)</td>
<td>1628.97 (52.64)</td>
<td>1710.67 (195.00)</td>
</tr>
<tr>
<td>Pisiform</td>
<td>876.79 (55.87)</td>
<td>691.42 (35.23)</td>
<td>764.73 (12.35)</td>
<td>816.50 (143.54)</td>
<td>787.36 (78.67)</td>
</tr>
<tr>
<td>Scaphoid</td>
<td>2716.21 (193.51)</td>
<td>2222.55 (174.06)</td>
<td>2029.67 (39.35)</td>
<td>2087.47 (82.60)</td>
<td>2263.98 (312.13)</td>
</tr>
<tr>
<td>Trapezium</td>
<td>2395.46 (161.47)</td>
<td>1890.28 (136.32)</td>
<td>2422.07 (80.39)</td>
<td>1696.78 (172.38)</td>
<td>2101.15 (364.05)</td>
</tr>
<tr>
<td>Trapezoid</td>
<td>1480.87 (104.38)</td>
<td>1002.22 (98.15)</td>
<td>1138.47 (60.76)</td>
<td>964.85 (70.76)</td>
<td>1146.60 (235.01)</td>
</tr>
<tr>
<td>Triquetrum</td>
<td>1427.32 (155.94)</td>
<td>1273.57 (79.83)</td>
<td>1401.87 (29.55)</td>
<td>1524.42 (50.09)</td>
<td>1406.79 (103.33)</td>
</tr>
</tbody>
</table>

Discussion

The mean surface areas and volumes of carpal bones and standard deviations of repeated measures were consistent with other studies (Patterson et al., 1995; Neu et al., 2000; Wolfe et al., 2000; Crisco et al., 2005). Despite improvements in automatic segmentation of CT images (Sebastian et al., 2003), the small and irregular shapes of the carpal bones and the narrow joint spaces separating these bones limit the effective use of fully automatic segmentation software. Manual editing of the images...
produces variations in the shape of the surface models, affecting the results of the registration. Our results show that the errors due to manual editing are relatively small and that the intraoperator variability in the surface models was greater than the interoperator variability.

Registering surface models to each other using principal axes averages the surface data and is easily applied. The resulting registration errors, however, are larger than those that can be explained by the intra- and interoperator variations found in this study. Conversely, ICP takes advantage of all surface features. This explains the improvement found in registration using ICP. Differences in alignment between ICP and principal axis registrations were least for the relatively asymmetrical scaphoid and greatest for the more symmetrical pisiform. These findings are supported by the work of Neu and coworkers (2000).

However, ICP requires larger computational resources (approximately five minutes on a Pentium PC with 2 GB of memory) and a good initial approximation. Such initial approximations are often tedious and time consuming to provide using manual positioning.

ICP based on an initial approximation from principal axes provided a reliable and accurate registration for all carpal bones in this study with minimal user intervention. Registration for carpal bones based solely on principal axes should be avoided.

Acknowledgments

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References


