Kinematic Accuracy of Three Surface Registration Methods in a Three-Dimensional Wrist Bone Study

The use of registration techniques to determine motion transformations noninvasively has become more widespread with the increased availability of the necessary software. In this study, three surface registration techniques were used to generate carpal bone kinematic results from a single cadaveric wrist specimen. Surface contours were extracted from specimen computed tomography volume images of the forearm, carpal, and metacarpal bones in four arbitrary positions. Kinematic results from each of three registration techniques were compared with results derived from multiple spherical markers fixed to the specimen. Kinematic accuracy was found to depend on the registration method and bone size and shape. In general, rotation errors of the capitate and scaphoid were less than 0.5 deg for all three techniques. Rotation errors for the other bones were generally less than 2 deg, although error for the trapezoid was greater than 2 deg in one technique. Translation errors of the bones were generally less than 1 mm, although errors of the trapezoid and trapezium were greater than 1 mm for two techniques. Tradeoffs existed in each registration method between image processing time and overall kinematic accuracy. Markerless bone registration (MBR) can provide accurate measurements of carpal kinematics and can be used to study the noninvasive, three-dimensional in vivo kinematics of the wrist and other skeletal joints. [S0148-0731(00)01105-5]

Keywords: Error Analysis, Registration, Kinematics, Three-Dimensional

Introduction

Quantification of carpal kinematics is technically challenging due to the small size, complex shape, and tight articulating surfaces of the individual bones. Carpal kinematics have been previously described in vitro using a variety of techniques, including biplanar radiography [1–3], electromagnetic sensors [4], and high-speed video data acquisition systems [5]. These techniques utilize invasive procedures, such as the embedding of radiopaque or other markers in individual bones. As a result, specimen anatomy is disrupted, which may possibly alter normal carpal kinematics. Recently, an approach has been described for the full three-dimensional, noninvasive study of in vivo carpal kinematics [6]. This study employs surface registration methods, which refers to the kinematic matching of object surfaces through unique rigid body motion transformations, for the description of bone motion between subsequent computed tomography (CT) volume image scans. This noninvasive, in vivo approach provides the ability to answer questions that cannot be addressed with in vitro methods, such as the impact of surgical intervention, implementation of muscular forces and the effects of healing on bone kinematics. A comprehensive knowledge, however, of the accuracy of this approach has not yet been reported.

The purpose of this study is to evaluate and compare the accuracy associated with three registration techniques: (1) an inertia matching technique developed for the efficient calculation of three-dimensional bone physical properties [7], (2) a surface matching technique first described for the registration of brain CT, positron emission tomography, and MRI images [8], and (3) a surface matching technique incorporated into the biomedical imaging software Analyze™ (Mayo Biomedical Imaging Resource, Rochester, MN). The three techniques were used to generate kinematic results from a single cadaveric specimen. The results were compared to the motion of multiple spherical markers, which were used as a registration “gold” standard.

Methods

Data Acquisition

Specimen Preparation. A single formalin-fixed cadaveric specimen (left wrist, male, age 65) was used, which consisted of two components: the hand, composed of all eight carpal bones and the proximal portions of four metacarpals (two–five), and the forearm, which contained approximately the distal third of the radius and ulna. Skin and other tissues were dissected from each component to expose individual bones and their ligamentous connective tissues. Each component was encased in plastic resin to prevent relative motions between any bones. Additionally, seven radiopaque ceramic spheres of various high-tolerance diameters (ranging from 6.35 to 19.05±0.002 mm) and a keyed-dowel were rigidly glued to each component with epoxy (Fig. 1). The centroids of seven spherical markers allowed for the calculation of specimen rigid body motions by a method of least-squares [9] and were used as the registration “gold” standard. The keyed-dowel allowed each component to be rigidly fixed in various positions to a specially designed polycarbonate positioning jig.

Image Acquisition and Segmentation. The specimen components were each placed in four separate positions within the polycarbonate jig. The specimen was axially scanned in the four positions using computed tomography (CT) (Hispeed Advantage, GE Medical Systems, Milwaukee, WI). Volume images were obtained with the voxel dimensions of 0.234×0.234×1 mm³. Cortical bone and sphere contours were extracted from raw CT images using Analyze™ software (Mayo Foundation, Rochester, Pennsylvania).
Contours were identified and associated to define the individual spheres and bones using custom MATLAB software (Mathworks, Natick, MA).

Spheres. Sphere centroids and volumes were calculated using equations already developed [7]. Specimen components and fixed spherical markers were assumed to behave as rigid bodies. The specimen rotation and translation transformations were obtained using the centroids of spherical markers attached to each cadaveric component and a least-squares algorithm [9].

Registration Methods. Bone surfaces were registered using three techniques: (1) an inertia matching technique [7], (2) a surface matching technique first described for registration of brain images [8], and (3) a surface matching technique incorporated into the biomedical imaging software Analyze™ (Mayo Biomedical Imaging Resource, Rochester, MN).

Inertia Registration (Inertia). The transformation of a rigid bone between two positions was determined by matching the bone’s principal axes of inertia and centroid. The principal axes of inertia, which are invariant under a change in bone orientation or position, were calculated as eigenvectors of the symmetric mass moments of inertia matrix [7]. The centroid and volume were also determined using the approach previously reported [7]. Principal inertia magnitudes were the three eigenvalues of the mass moments of inertia matrix. The rotation matrix and translation vector of the rigid bone were then calculated using the respective principal axes of inertia and the centroid. The inertia technique was used to determine the kinematic transformations for eight carpal bones, since only their geometry was completely obtained during scanning. The ratio of second and third principal inertia magnitudes was also calculated. As the ratio approaches unity, bone shape approaches that of a cylinder whose orientation of the second and third principal axes are undefined.

Surface Registration 1 (Pelizzari). The kinematic transformation of a bone between two positions was determined by minimizing the root mean square misfit of the bone surfaces [8]. In this technique, an iterative algorithm was used to produce congruent bone surfaces and the resulting kinematic transformations. The technique is semi-interactive, such that a user is able to modify one or more of the transformation parameters, visually verify anatomic feature alignment, and continue activation of the minimization algorithm to avoid local minima solutions and produce an optimal surface match. This technique is applicable to bones with variations in volume image scans, such as the radius, ulna, and metacarpals, since surface alignment does not depend on the acquisition of complete bone geometry. The Pelizzari method was used to calculate kinematic values for the radius, ulna, eight carpal bones, and third metacarpal. Additionally, three independent users each applied this method ten times to the radius for two kinematic comparisons to measure the reproducibility and inter-observer variability of the technique.

Surface Registration 2 (Analyze™). A three-dimensional registration algorithm incorporated into Analyze™ software was also used to determine the transformation of bone surfaces. The algorithm is based on chamfer matching and minimization of a root mean square cost function [10]. This method is applied automatically to match binary bone volume images thresholded from raw images.
CT images. The cost function to be minimized is derived from the root mean square average of distance values between points sampled on bone surfaces. The algorithm searches iteratively though six-parameter space to achieve a global minimum. Additional image processing was required with this method, whereby all data, except the specific bone to be analyzed, was manually deleted from the raw CT images. Also, bone transformations in the Analyze™ method were reported in a left-handed coordinate system, so it was necessary to convert the values to a right-handed system for comparison with other registration methods. The Analyze™ method was used to determine values for the radius, ulna, scaphoid, lunate, and capitate.

Data Analysis. The four specimen positions allowed for six independent kinematic comparisons. Rotation and translation transformations obtained from each technique were converted into helical axis of motion (HAM) parameters [11], defined by the rotation about and translation along a unique axis in space. The distances between sphere centroids were calculated in each position and compared over all positions to verify rigid body assumptions. Dependence of sphere marker choice on motion calculations was estimated by using different numbers and groupings of spheres to generate the HAM rotation and translation parameters.

Four variables were determined from HAM parameters for the comparison of registration techniques. Two variables, the rotation about and the translation along the helical axis, were obtained directly from the conversion to HAM parameters. The absolute difference between bone and ceramic sphere HAM rotation and translation parameters for a given kinematic comparison were calculated. These values are referred to as rotation error and translation error, respectively. HAM orientation error was defined as the angle between bone and spherical marker helical axes. HAM orientation error was calculated using the inner product of the two orientation vectors. HAM distance error was defined as the minimum distance between the bone and spherical marker helical axes. Rotation error, translation error, HAM orientation error, and HAM distance error allows for a complete description of error in HAM parameters. Finally, differences in rotation error values for the three registration methods were compared by performing an ANOVA with multiple Tukey–Kramer post tests (Instat, Graphpad, San Diego, CA).

Results

Spheres and Volumes

Sphere Error. The distances between all possible pairs of spheres (n=21 for each specimen component) varied less than 0.04 mm over the four scan positions. Thus, the specimen components were assumed to move as rigid bodies, allowing for direct comparisons of sphere and bone motion. The number and grouping of spherical markers influenced motion calculations (Fig. 2). When four or more markers were used to calculate specimen motion, the standard deviation of HAM rotation and translation parameters was less than 0.1 percent of the mean. In order to maximize accuracy, all seven spherical markers were used to generate the "gold standard" motion values.

Volumes. Sphere volumes varied by diameter and scan position. The percent error from the manufacturer’s specifications ranged from 2.5 percent for the largest spheres to 7.0 percent for the smallest spheres. Bone volume standard deviation for the eight carpal bones was found to range from 0.8 percent of the mean for the larger bones (mean volume=2966 mm³) to 4.8 percent of the mean for the smaller bones (mean volume=669 mm³) over the four scanned positions. Bone volume was found to correlate linearly with rotation error ($r^2=0.5079$, $p=0.0473$) and HAM orientation error ($r^2=0.7228$, $p=0.0075$) (Fig. 3). Bone volume variation was not calculated for the radius, ulna, or metacarpals because the scanned portions of these bones varied between positions.

Inertia Magnitudes. The standard deviation in carpal bone second and third principal axis magnitudes was less than 1.5 percent of the mean over the four positions. Rotation error and HAM orientation error was plotted versus the ratio of the second and third principal axis magnitudes (Fig. 4). As the ratio of inertia magnitudes approached unity, the magnitude of error values increased. In bones with inertia magnitude ratios greater than 0.9, the increase in error value magnitudes was dramatic, while in bones with inertia magnitude ratios less than 0.9, clear trends did not exist in plotted results. The bones with the highest and lowest inertia magnitude ratios (trapezoid and hamate, respectively) are shown in Fig. 5.

![Fig. 2](image-url) Fig. 2 The low standard deviation of rotation about and translation along the helical axis for different numbers and all possible combinations of spherical markers fixed to the specimen hand component indicates the validity of assuming the spheres moved as a rigid body. Rotation and translation values are shown for a typical motion. The mean and standard deviation values for three spheres in the translation along the helical axis were −24.5 mm and 24.5 mm, respectively (not plotted).
Error Parameters. Error values varied by bone and registration technique. Values for rotation error calculated using the inertia technique were not significantly greater \((p > 0.05)\) than values calculated using either the Pelizzari or Analyze™ technique for all bones except the trapezoid \((p = 0.0199, \text{ mean difference } = 2.17 \text{ deg})\). Also, values calculated using the Analyze™ technique were typically small relative to the other two techniques (Figs. 6–9).

Inertia. Carpal bone rotation error was generally less than 2.0 deg, although trapezoid rotation error was larger than 3.0 deg (Fig. 6). Bone translation error was generally less than 1.0 mm, although values for both the trapezoid and trapezium were greater than 1.0 mm (Fig. 7). HAM orientation error was less than or approximately equal to 5.0 deg for most bones (Fig. 8). Large HAM orientation errors were observed in both the trapezoid and pisiform. Although one abnormally large angle between the pisiform and spherical marker helical axes resulted in the observed mean and standard deviation, all other mean HAM orientation errors were less than 10.0 deg. All HAM distance errors were less than 0.3 mm (Figs. 8 and 9).

Pelizzari. Bone rotation errors were less than or approximately equal to 1.0 deg (Fig. 6). All bone translation errors, with the exception of the trapezium, were less than approximately 0.7 mm. Trapezium translation errors were greater than 1.0 mm (Fig. 7). HAM orientation and HAM distance errors for all bones were less than 5.0 deg and 0.3 mm, respectively (Figs. 8 and 9).
Pelizzari technique was found to be highly reproducible and independent of observer. The rotation and translation error of the radius was found to less than $0.1 \pm 0.4$ deg and $0.5 \pm 0.3$ mm, respectively, for all observers.

Analyse™ Rotation and translation errors were less than 1.0 deg and 1.0 mm, respectively (Figs. 6 and 7). Calculated HAM orientation and HAM distance errors were less than approximately 3.0 deg and 0.3 mm, respectively (Figs. 8 and 9).

Discussion

This study evaluated the accuracy of three surface registration methods in a single cadaveric specimen. Arbitrary kinematics of the radius, ulna, third metacarpal, and carpal bones were determined using three surface registration techniques and compared to spherical marker motion. Although this work was focused on evaluating registration accuracy, errors introduced due to segmentation and image acquisition could not be isolated and certainly affected results. Our maximum calculated variation in bone volumes over all positions was less than 4.8 percent, however, indicating a minimal influence of segmentation errors on registration results. A higher specimen scan resolution will also aid in segmentation accuracy and compounding errors. Additionally, recent developments in automated segmentation algorithms specifically designed for the wrist may decrease segmentation error and potential inter-observer variability [12].

Kinematic accuracy of the surface registration techniques was determined by comparison with the spherical markers, whose centroid location could be calculated at subvoxel resolution. A previous study of centroid localization in CT images showed residual fit errors of less than 0.03 mm by comparing CT marker locations with positions measured using a roentgen stereogrammetric analysis [13]. Centroid accuracy was also a function of the number of voxels used to define the sphere. The markers in this study consisted of between approximately 750 and 6950 voxels, depending upon the size of the spherical marker. Considering the large number of voxels, the specimen rigidity and the use of the least-squares fit for seven markers, it is reasonable to conclude that errors in the kinematics determined with the spherical markers were insignificant. The bone motions we analyzed in this study were clearly nonphysiological, but were constructed to bracket a broad range of possible motions. Thus, while actual physiological carpal bone motions will certainly differ from these motions, we believe that the present analysis provides a good estimate of the errors that occur in vivo.

The inertia technique was the most efficient method to register bones with fully defined surfaces, such as the carpal bones. Using this technique, error was smallest for the scaphoid and capitare...
and varied for other bones, with noticeably larger errors for the pisiform, trapezoid, and trapezium. The larger errors in the pisiform, trapezoid, and trapezium were attributed to symmetry about their major axes, as the ratio of inertia magnitudes for these bones approached unity. Additionally, inertia registration was invalid when the extent of the bone surface varied between scans (such as with the radius, ulna, and metacarpals), creating inconsistent principal axes and centroid descriptions.

The Pelizzari and Analyze™ techniques were advantageous over the inertia technique in the case of bones with incompletely defined surfaces (e.g., radius, ulna, and third metacarpal). Accuracy was generally better than the inertia technique, although a dependence on bone type existed. The Pelizzari technique required user interaction in visually matching surfaces; the Analyze™ technique demanded extensive volume image preparation time, although the matching algorithm was automated. Even though the Analyze™ technique was only used to explore errors with selected bones, we expect the accuracy for other bones to follow trends similar to the other two registration methods.

Registration accuracy results associated with several current techniques are typically described by others in terms of a residual misfit, normally expressed as a root mean square misfit distance (rms, mm) [8,13,14]. However, it is unclear how these reported accuracy results might influence kinematic measurements. Additionally, the lack of error analysis for all carpal bones and helical axes parameters in the literature limits a full comparison of our results to other kinematic methods. The helical axis orientation and position remain largely undefined; however, rotation and translation components are reported for various studies with associated methodological accuracy and are thus available for comparison. The three-dimensional roentgen stereophotogrammetric method developed by Selvik [15] has a reported variance of 0.7 deg and 0.08 mm. This method was used by de Lange et al.[16] to measure the three-dimensional kinematic characteristics of selected carpal bones in two human cadaveric wrist joints. A similar radiographic technique has been used to describe elbow [17] and carpal [1,18,19] kinematics with a demonstrated accuracy within 2.0 deg and 0.4 mm. Recently, a magnetic tracking device was used to measure the dynamic motion of individual carpal bones [4] with rotational errors up to 2.0 deg. With respect to these various techniques, our accuracy measurements most closely agree with those reported for planar radiographic and magnetic tracking device techniques. Furthermore, a three-dimensional technique for measuring dynamic knee replacement kinematics has a reported accuracy of 1.0 deg and 0.5 mm [20]. This single-plane fluoroscopy technique is not applicable to small, tightly packed wrist structures and requires surface models with known geometries for kinematic calculations.

Our previously described noninvasive markerless bone registration (MBR) approach [6] uses the Inertia and Pelizzari registration methods studied here to measure in vivo three-dimensional carpal kinematics and has been applied to study in vivo wrist flexion-extension [21,22]. The error analysis outlined here provides a detailed estimate of the accuracy for these and future in vivo kinematic studies. Ultimately, MBR techniques may be used to help answer questions that previous noninvasive methods were unable to address, such as the long-term effects of surgical intervention and healing on joint function.

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References