Visualization of the Gap in Scapholunate Joint

Haoyu Wang
Department of Manufacturing & Construction Management
Central Connecticut State University
1615 Stanley Street, New Britain, CT 06050

Frederick W. Werner, Jason K. Green, and Walter H. Short
Department of Orthopedic Surgery, SUNY Upstate Medical University
505 Irving Ave., Syracuse, NY 13210

ABSTRACT - Instability of the scapholunate joint is frequently manifested by wrist pain and is sometimes visualized by a 2 to 4 mm gap between the scaphoid and lunate. Surgical repairs have had limited success, in part due to the surgeon being unsure which ligament or ligaments have been torn until the time of surgery. Various methods have been used to describe this gap between the bones and various levels of instability have been described. Ideally a surgeon would have an imaging technique (x-ray, CT scan or MRI) that would help in determining which ligaments have been damaged by visualizing the gap between the bones. We proposed and implemented three measurements, a 1D minimum gap between the bones, a 2D area descriptor of the gap (fig. 4), and a 3D volume descriptor of the gap (fig. 5). Cadaver wrists were moved through cyclic flexion-extension (FE) and radioulnar deviation (RU) motions under computer control. Three dimensional scaphoid and lunate motion data were collected in the intact specimens and after sequentially sectioning three ligaments, in two sequences. Data were again collected after 1000 cycles of motion to mimic continued use after injury. CT scan images of each wrist were contoured and stacked with imaging software. The surface models (dxf) were converted to solid objects (IGES). A DLL (Dynamic Link Library) was created in C++ to interface with SolidWorks®. The experimentally collected kinematic data of the carpal bones were used to move the virtual bone models through the DLL in SolidWorks®. The articulating surface on each bone is a 3D surface with 3D curves as boundary. The 1D, 2D, and 3D gaps are created and calculated by the DLL in SolidWorks® automatically while the scaphoid and lunate are in motion. They can help the surgeon in better visualizing the injury.

I. Introduction

Damage to the ligaments of the wrist is a common injury, but one that is not well publicized. In 1999, traumatic wrist injuries were reported by 88,000 workers in private industry and by 580,000 people whose ligamentous injuries were related to consumer products1,2. In particular, injuries due to recreational activities such as snowboarding, skateboarding, and riding scooters has increased at a rate of 15% per year.

One region of the wrist that is commonly injured after falling on an outstretched hand is the scapholunate (SL) joint (Figure 1). An impact to the wrist may produce carpal instability where the stabilizing

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1 Bureau of Labor Statistics
2 National Electronic Injury Surveillance System (NEISS)
ligaments of the wrist are compromised (Figure 2). The instability pattern between the scaphoid and lunate may cause pain and the inability to grasp tools or lift objects. As noted by Garcia-Elias et al (2006) the adverse effects of the ligament tears are underestimated and the injury is frequently untreated or poorly managed. Numerous surgical treatments have been developed with varying success (Manuel, J. et al, 2007).

The purpose of this study was to develop a methodology to determine if various joint gap measurements between the scaphoid and lunate could be related to specific ligament injuries through three-dimensional (3D) computer models of the scapholunate joint. 3D models are useful tools for the study of complex joint motions. In vitro 3D animations and models have been based on motion of the forearm at various static positions (Fischer et al., 2001), dynamic vertebral motion (Crip ton et al., 2001), passive motion of extremities (Van Sint Jan et al., 2002), and passive motion of carpal bones (Patterson et al., 1998). In vivo motions have been modeled using biplanar radiographs at static joint angles (Asano et al., 2001), high-speed biplanar radiographs in a canine (You et al., 2001), and 3D model fitting of fluoroscopic videos (Dennis et al., 1996). Multiple in vivo 3D CT data sets, taken at various static joint positions, have been animated by Crisco et al. (1999) and Snel et al. (2000). These different techniques have quantified and illustrated rotation angles, motion axes, contact areas, and ranges of motion.

Although each method has its inherent benefits, no single technique animates dynamic human joint motion with commercial software. Static and passive motion studies may not account for kinematic changes due to dynamic tendon loads, and the need for custom software development can be overwhelming. The goals of this paper were to present a technique to (a) Develop methodology to characterize separation of scaphoid and lunate with ligamentous sectioning, (b) Determine which wrist positions might best differentiate these effects. These interbone gaps help describe bone motions and kinematic changes due to ligamentous injury.

II. Methods and Materials

A servo-hydraulic simulator was used to move cadaver hands through repeatable wrist motions (Short et al., 2002a, b; Werner et al., 1996). Fastrak motion sensors (Polhemus, Colchester, VT) collected kinematic data at 27 Hz for the scaphoid, lunate, and radius, and at 82 Hz for the 3rd metacarpal. A wrist flexion-extension motion (50° of third metacarpal flexion to 30° of extension) and a radial-ulnar deviation motion...
(10° radial to 20° ulnar) were done. After testing, each arm was removed from the simulator and rigidly fixed within a Styrofoam box using expanding urethane foam. Fastrak kinematic data were collected and the arm was CT scanned. The post-test kinematic data were used to establish a spatial relationship between the sensor data and the location and orientation of the bones in the CT slices (Figure 3).

CT reconstruction  Polygon model  Solid model

Figure 3. CT slice model, polygon model, and solid model

The CT images were segmented with SliceOmatic imaging software (Tomovision, Montreal, Canada) to produce surface shells (polygonal models) of the bones. This software uses a proprietary algorithm to automatically contour regions of high gray-level contrast. The user traces an area by using a mouse and cursor to place points around the structure to be contoured. The algorithm then uses the original gray-level gradient of the image to place a contour near the user-selected points, based on the highest contrast in that immediate area. The user-selected points are replaced with software-generated points along the gradient that are spaced at two pixels apart. The user can limit the amount of curvature allowed in the contour. For this study, the carpal bones were contoured at the subchondral bone/cartilage interface and at the outer edges of the magnetic coils for the sensors.

To calculate interbone gaps, the polygonal bone models were exported from 3DStudio-MAX and converted to NURBS (Non-Uniform Rational B-Spline) surface models using Geomagic Studio (Raindrop Geomagic, Research Triangle Park, NC). NURBS (.igs) are smooth continuous surfaces defined over a quadrilateral region based upon vertex points and allow the models to be analyzed with three-dimensional CAD software. The polygons were decimated, refined and replaced with a grid pattern to fit a closed surface. The surface consisted of 1000 patches per bone.

Animations of the bones’ solid models and interbone gaps calculations for each frame of an animation were implemented in Solidworks 3D CAD software (Solidworks Corp., Concord, MA). We have developed in-house software, ORTHOPEDICS, in C++, using the SolidWorks API (Application Programming Interface) on a Windows platform. The software has the form of DLL (Dynamic Link Library) which is easily loaded and unload in SolidWorks just like any other standard add-ins.

ORTHOPEDICS automatically created separate CAD assemblies, based upon the Fastrak carpal data, to replicate each animation frame produced in 3DStudioMAX. Instead of the conventional rotation matrix, Quaternions are used in calculating motions of carpal bones (scaphoid and lunate) because they are more efficient and more numerically stable. For each assembly, the software computed 1D, 2D, and 3D interbone gaps between scaphoid and lunate.

1. 1D gap calculation

We define the 1D gap as the minimum distance between the carpal bones. The minimum distance is calculated by what we call a “pingpong algorithm.” The top image in Figure 4 illustrates this method. If we open and separate the bones like a book, we can see the articulating surfaces as in the lower image in Figure 4. The SolidWorks API is capable of locating a point on a face that is closest to a point in the space. We start from a point that is in between the scaphoid and lunate. We
can get a point on one of the articulating faces of scaphoid. Now use this point as the starting point to find the closest point on the face of the lunate. For each patch-to-patch comparison, points were compared based upon a user-defined spacing (tolerance) of 1 mm. The algorithm searched for an individual point in one patch that was closest to a second point on the other bone. It ‘ping-ponged’ between these two patches (one point to another point) until the newest point on one patch was within 1mm of the previous point. To increase the efficiency of the algorithm, the user selected the patches to be examined for distance computation. A line was drawn between the bones to represent the minimum distance, and the CAD assembly saved. The algorithm created the next assembly in the motion, calculated the minimum distance, and saved the distances to a text file. Methods of validation of the minimum distance can be found in (Green, J et al, 2004).

2. 2D gap calculation

2D gap is defined as a quadratic area between the carpal bones. This was inspired by the regular practices of hand surgeons when they diagnose these kinds of injuries. Figure 5 shows the two dorsal points and two volar points picked by the user (normally a hand surgeon). The dorsal separation and volar separation were calculated. Three of the four points were used to define a plane. The fourth point was projected to the plane. Then the quadratic area was calculated.

The user can otherwise pick four points that detect the distal and proximal separations (Figure 6). In this
3. 3D gap calculation

3D gap is defined as the lofted volume between the articulating surfaces of the carpal bones (Figure 7). Since CAD software can only calculate the volume and surface area of a complex shape when the model is a solid, it was necessary to first describe a contained volume between the scaphoid and lunate. As the articulating surface on each bone is a 3D surface with a 3D curve as a boundary, we chose to use the idea of lofting to generate the volume between the two articulating surfaces. Lofting creates a feature by making transitions between profiles. Using the lofting method to generate the volume has two advantages. First, the 3D boundary curves and 3D surfaces of both articulating surfaces are used directly instead of being approximated when generating the volume. Second, we have the flexibility to change the definition of the volume by changing the guide curves of the loft. For any frame of motion of the carpal bones, the volume between the articulating surfaces is generated physically by using the Solid Lofting feature provided in SolidWorks.

There are five ligaments that are thought to stabilize the scaphoid and lunate. The scapholunate interosseous ligament (Figure 8), known as SLIL, connects the scaphoid and lunate. On the dorsal side of the wrist, there are the dorsal intercarpal ligament, known as DIC, and the dorsal radio carpal ligament, known as DRC. On the volar aspect of the wrist, there are the radioscapho-capitate ligament, known as RSC and the scapho-trapezium ligament, known as ST.

Figure 7. 3D gaps (lofted volume)

Figure 8. Ligamentous stabilizers

In each of 19 fresh frozen cadaver forearms that were tested for this study, we mounted Fastrak electromagnetic motion sensors onto the scaphoid, lunate, third metacarpal, and distal radius to measure their 3D motion and electromagnetic sources were mounted onto a platform attached to the ulna.

Four groups of arms were studied. For each group of arms, three ligaments were sequentially sectioned in the sequences shown below.

**Group 1:** SLIL, RSC, ST, 1000 cycles of motion - 5 arms
**Group 2:** ST, SLIL, RSC, 1000 cycles of motion - 4 arms
**Group 3:** DRC, DIC, SLIL, 1000 cycles of motion - 5 arms
**Group 4:** DIC, SLIL, DRC, 1000 cycles of motion - 5 arms
We measured the motion of the scaphoid and lunate with the wrist intact, after each ligament was sectioned for each of the 3 sequences shown here, and after 1000 cycles of motion.

III. Results

During wrist flexion/extension (Figure 9), the minimum distances were computed for each level of sectioning. Increase of the minimum distance was observed only when SLIL was sectioned. This was accentuated with sectioning of the RSC ligament and even more so with the addition of 1000 cycles of repetitive motion. It is important to note that the maximum gap always occurred during wrist flexion.

Figure 10 shows another average minimum distance plot during wrist flexion/extension but with a different sectioning sequence. Increase of minimum distance happened only after the SLIL was sectioned. A further increase was observed after 1000 cycles of motion. Again the maximum gap measured by minimum distance appeared during wrist flexion.

During radial/ulnar deviation, an increase in the minimum distance was observed only after SLIL was sectioned. In addition, maximum value of the minimum distance was detected in ulnar deviation.

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Figure 11 shows the dorsal view of the wrist joint as if we were making measurements on an X-ray. The distance A and B look similar in length. But actually they have very different lengths (Figure. 12). It is better illustrated from this view. This is why the minimum distance in this study based on the 3D model is a much better descriptor than the distance measured in 2D on an X-ray.

Measurement of the dorsal and volar gaps between the scaphoid and lunate showed an increase in the distance between the scaphoid with ligamentous sectioning (Figure. 13). This graph shows the % increase in gap after all ligaments have been cut and after 1000 cycle. As shown here in this series of arms, the dorsal and volar distances increased the most in wrist flexion after all the ligaments were sectioned. Also the dorsal gap increased more than the volar gap. The bones did not separate evenly.

The distances between the proximal and distal points on the articulating surfaces also increased with ligamentous sectioning (Figure 14). As shown here, the increase was greater in flexion than in extension and the dorsal distance increased more than the proximal distance during only a small part of the motion.

V. Conclusions

Our conclusions of this study are:
1) Changes in carpal bone position are better detected using 3-D visualization techniques.
2) Accuracy of measuring a scapholunate gap on a 2-D x-ray with the wrist positioned in neutral is questioned.
3) Three methodologies have been developed to characterize these changes (minimum distance, four point area, and volume).

4) Changes due to DIC or ST sectioned alone were not yet detected.

5) Detection of major SL gap changes may be best detected in wrist ulnar deviation and flexion.

VI. References


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