AN INNOVATIVE APPLICATION OF 3D CAD FOR HUMAN WRIST LIGAMENTOUS INJURY DIAGNOSIS

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Abstract

Instability of the scapholunate joint is frequently manifested by wrist pain and is sometimes visualized by a 2-4 mm gap between the scaphoid and lunate. Surgical repairs have had limited success, due in part 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 such as x-ray, CT scan or MRI that would help in determining which ligaments have been damaged by visualizing the gap between the bones. In this study, the authors proposed and implemented three measurements: a 1D (one-dimensional) minimum gap between the bones, a 2D (two-dimensional) area descriptor of the gap, and a 3D (three-dimensional) volume descriptor of the gap. 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 after which the surface models (dxf) were converted to solid objects (IGES). Finally, 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 were automatically created and calculated by the DLL in SolidWorks®, while the scaphoid and lunate were in motion. These methods can help the surgeon in better visualizing the injury.

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 products [1, 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; see Figure 1. An impact to the wrist may produce carpal instability, where the stabilizing ligaments of the wrist are compromised, as indicated in 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. [1], 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 [2].

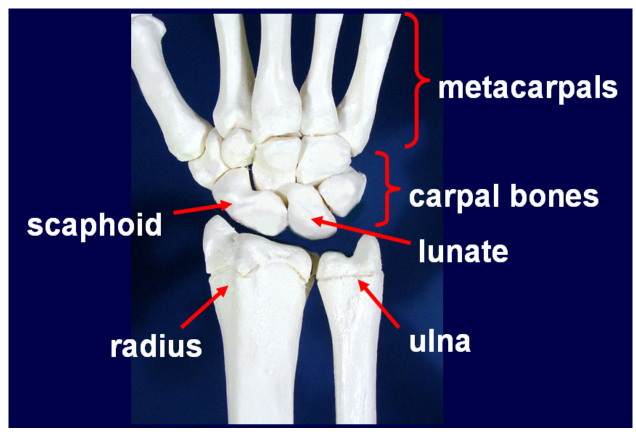

Figure 1. Scapholunate joint

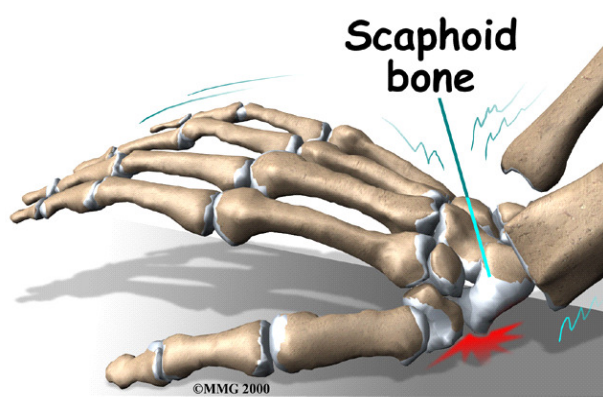

Figure 2. Stabilizing ligaments injury due to impact

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

[1] Bureau of Labor Statistics

[2] National Electronic Injury Surveillance System (NEISS)

injuries through 3D computer models of the scapholunate joint. Three-dimensional 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 [3], dynamic vertebral motion [4], passive motion of extremities [5], and passive motion of carpal bones [6]. In-vivo motions have been modeled using biplanar radiographs at static joint angles [7], high-speed biplanar radiographs in a canine [8], and 3D model fitting of fluoroscopic videos [9]. Multiple in-vivo 3D CT data sets, taken at various static joint positions, have been animated by Crisco et al. [10] and Snel et al. [11]. 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 study were to present a technique to (a) develop methodology to characterize separation of scaphoid and lunate with ligamentous sectioning and (b) determine which wrist positions might best differentiate these effects. These interbone gaps help describe bone motions and kinematic changes due to ligamentous injury.

Methods and Materials

A servo-hydraulic simulator was used to move cadaver hands through repeatable wrist motions [12]. 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 representing 50° of third metacarpal flexion to 30° of extension, and a radial-ulnar deviation of 10° radial to 20° ulnar were also performed. 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 a CT scan was performed on the arm. 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, as indicated in Figure 3.

The CT images were segmented with SliceOmatic imaging software (Tomovision, Montreal, Canada) to produce surface shells, or 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.

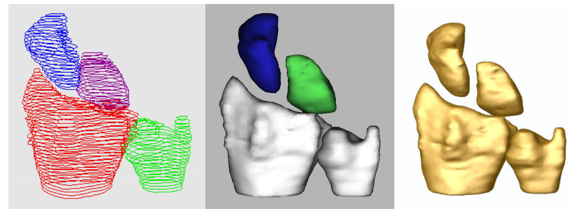

Figure 3. CT slice model, polygon model, and solid model

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. In order 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 [13]. 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.

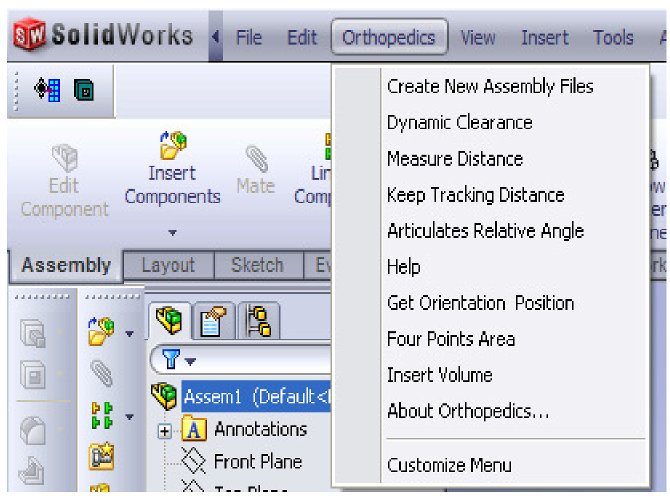

Figure 4. Orthopedics Add-in in SolidWorks

Animations of the bones' solid models and interbone-gap calculations for each frame of an animation were implemented in Solidworks 3D CAD software [14]. In this study, the authord developed in-house software, ORTHOPEDICS, in C++, using the SolidWorks API (Application Programming Interface) on a Windows platform; refer to Figures 4 and 5. The software has the form of DLL (Dynamic Link Library), which is easily loaded and unloaded in SolidWorks just like any other standard add-ins.

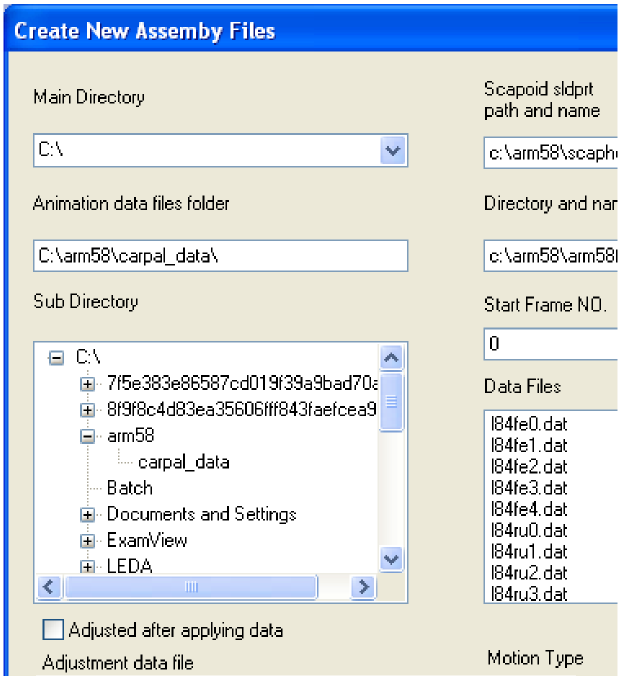

Figure 5. Orthopedics Dialog Box

ORTHOPEDICS automatically created separate CAD assemblies, based on the Fastrak carpal data, to replicate each animation frame produced in 3DStudioMAX. Instead of the conventional rotation matrix, Quaternions were used in calculating motions of the scaphoid and lunate carpal bones as 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

A 1D gap is defined as the minimum distance between the carpal bones. The minimum distance is calculated by what can be called a “pingpong” algorithm. The top image in Figure 6 illustrates this method. If the bones are opened and separated like a book, the articulating surfaces can be seen, as in the lower image in Figure 6. The SolidWorks API is capable of locating a point on a face that is closest to a point in the space. Starting from a point that is in between the scaphoid and lunate, a point on one of the articulating faces of scaphoid can be found. This point can now be used as the starting point for finding the closest point on the face of the lunate. For each patch-to-patch comparison, points were compared based on a user-defined spacing—or 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. Thus, it ‘ping-ponged’ between points on these two patches until the newest point on one patch was within 1 mm of the previous point. In order to increase the efficiency of the algorithm, the authors 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 [15].

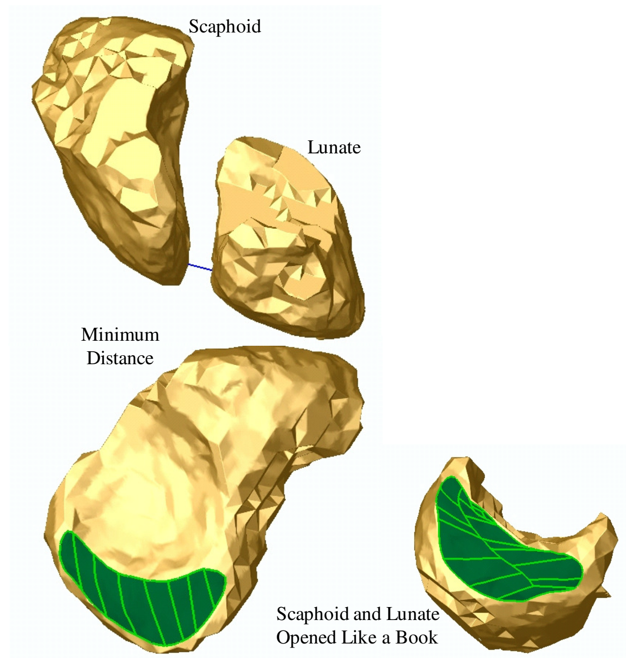

Figure 6. Ping-pong algorithm for 1D gap

2. Calculation of a 2D gap

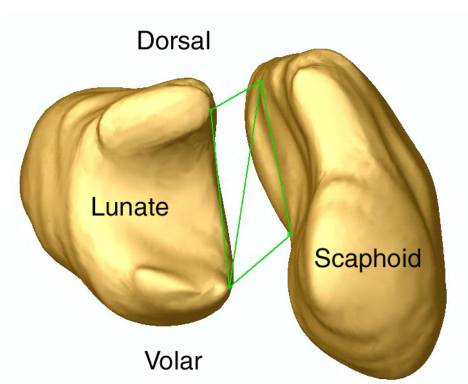

Figure 7. 2D gaps (dorsal and volar gaps)

A 2D gap is defined as a quadratic area between the carpal bones. This was inspired by the regular practices of hand surgeons as they diagnosed these kinds of injuries. Figure 7 shows two dorsal points and two volar points chosen ty the authors to represent a selection by a hand surgeon.. The dorsal separation and volar separation were then calculated.

Three of the four points were used to define a plane, while the fourth point was projected onto the plane. Then, the quadratic area was calculated.

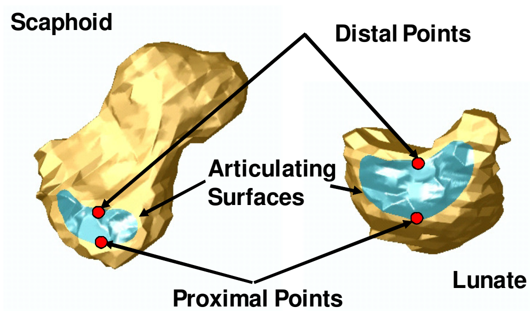

Figure 8. 2D gaps (distal and proximal gaps)

The user can otherwise pick four points that detect the distal and proximal separations, as indicated in Figure 8. In this figure, one can also see the articulating surfaces. These were used to generate the volume between the scaphoid and lunate.

3. Calculation of a 3D gap

A 3D gap is defined as the lofted volume between the articulating surfaces of the carpal bones; refer to Figure 9. 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, the idea of lofting was chosen 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, it offers the flexibility of changing 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, seen in Figure 10, known as SLIL, connects the sca

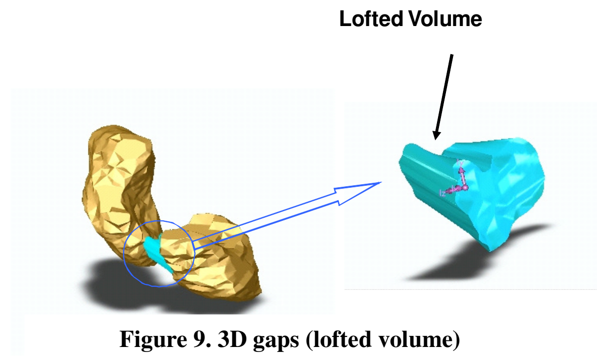

Figure 9. 3D gaps (lofted volume)

phoid and lunate. On the dorsal side of the wrist, is the dorsal intercarpal ligament known as DIC, and the dorsal radio carpal ligament known as DRC. On the volar aspect of the wrist is the radioscapho-capitate ligament known as RSC, and the scapho-trapezium ligament known as ST.

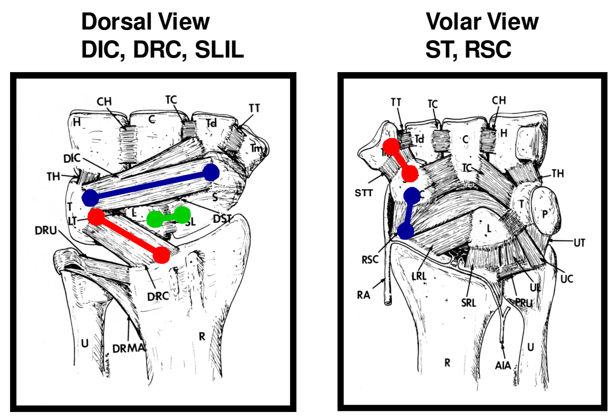

Figure 10. Ligamentous stabilizers

In each of 19 freshly frozen cadaver forearms that were tested for this study, Fastrak electromagnetic motion sensors were mounted onto the scaphoid, lunate, third metacarpal, and distal radius in order to measure their 3D motion with electromagnetic sources mounted onto a platform and 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, each of which saw 1000 cycles of motion.

Group 1: SLIL, RSC, ST, - 5 arms
Group 2: ST, SLIL, RSC, - 4 arms
Group 3: DRC, DIC, SLIL, - 5 arms
Group 4: DIC, SLIL, DRC, - 5 arms

The motion of the scaphoid and lunate was measured with the wrist intact, after each ligament was sectioned for each of the 3 sequences shown here, and after 1000 cycles of motion.

Results

Figure 11 shows the minimum distances computed for each level of sectioning during wrist flexion/extension. An 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 12 shows another average minimum distance plot during wrist flexion/extension but with a different sectioning sequence. An increase of the minimum distance occurred only after the SLIL was sectioned. A further increase was observed after 1000 cycles of motion. Again the maximum gap measured by the minimum distance appeared during wrist flexion.

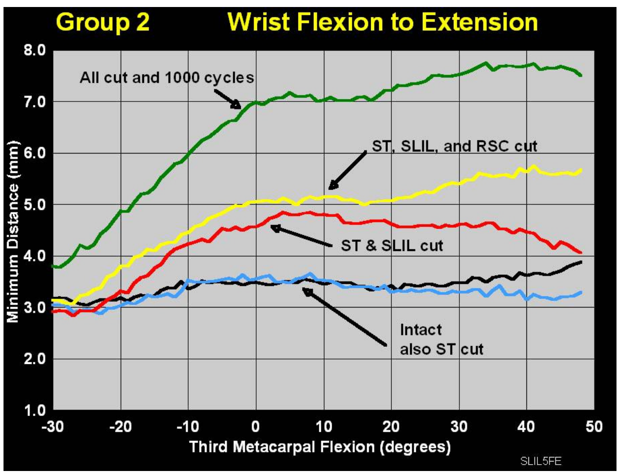

Figure 11. 1D gap after section of ST, SLIL, and RSC

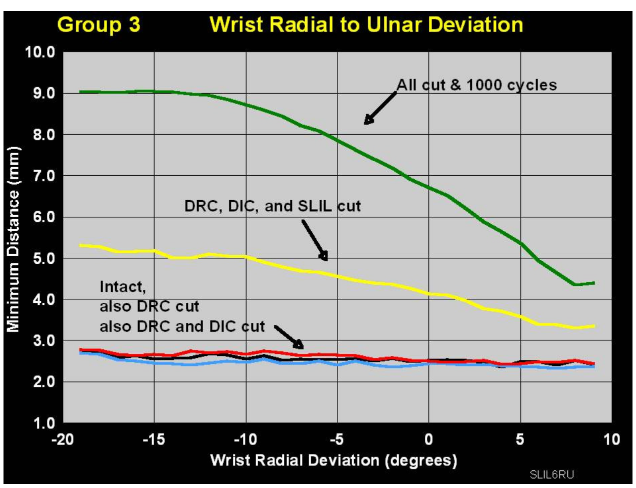

Figure 12. 1D gap after section of DRC, DIC, and SLIL

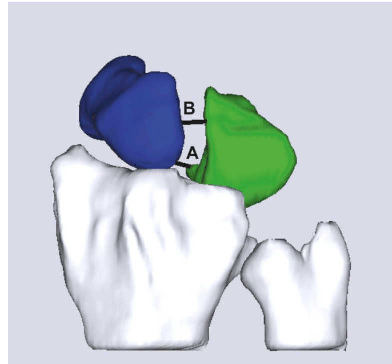

Figure 13. 1D gap as on an X-Ray

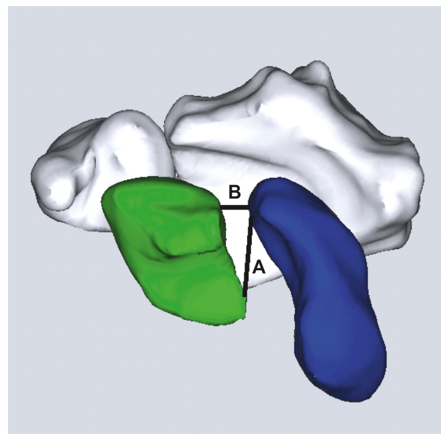

Figure 14. Actual 1D gap between carpal bones deviation

During radial/ulnar deviation, an increase in the minimum distance was observed only after SLIL was sectioned. In addition, the maximum value of the minimum distance was detected in ulnar deviation. Figure 13 shows the dorsal view of the wrist joint as if measurements were being made on an x-ray machine. Looking at Figure 14, distances A and B appear to be similar in length, when in fact they have very different lengths. 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. 15). This graph shows the percentage increase in the gap after all ligaments had been cut and after 1000 cycles. As shown in this series of arms, the dorsal and volar distances increased the most in wrist flexion after all of the ligaments were sectioned. Also, the dorsal gap increased more than the volar gap and the bones did not separate evenly.

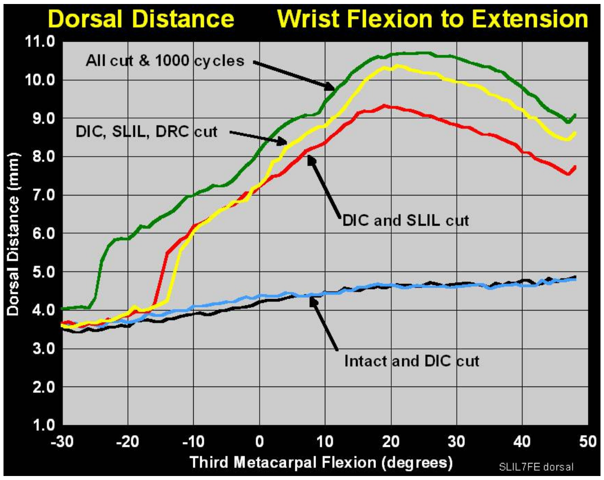

Figure 15. 2D dorsal gap

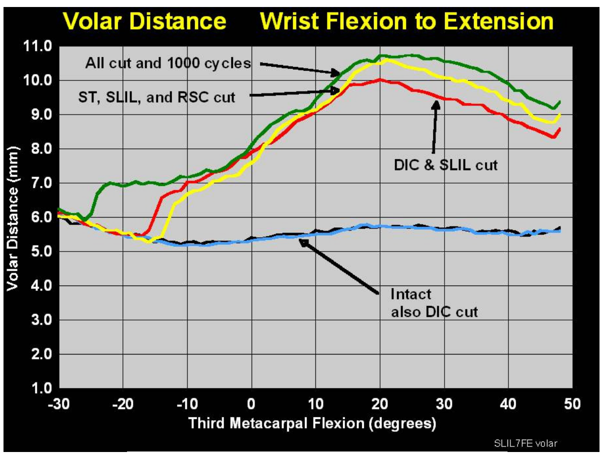

Figure 16. 2D volar gap

Looking at the graph in Figure 16, it can be seen that the distances between the proximal and distal points on the articulating surfaces also increased with ligamentous sectioning. Additionally, 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.

Volume changes I the gap during the wrist flexion/extension motion can be seen in Figure 17. The volume of the gap was greater in flexion and correlates well with the 1D minimum distance changes for both when the ligaments are intact and after all have been sectioned. Intuitively, one can consider volume as a better gap descriptor as it is 3D in nature and more

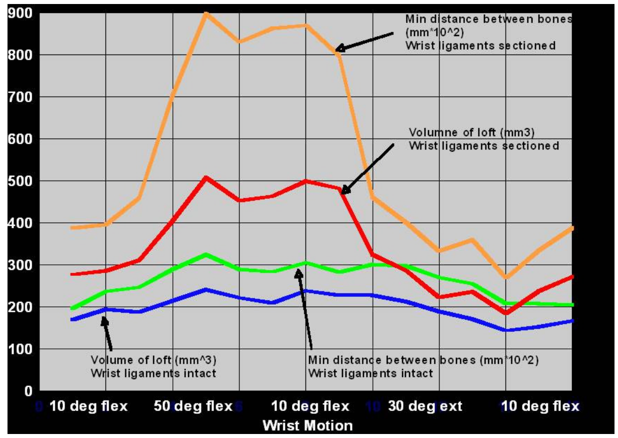

Figure 17. Correlation between 3D gap and 1D gap

nformative. How it could help in describing the gap between the scaphoid and lunate, is still under study.

Conclusions

This study showed that changes in carpal bone position are better detected using 3D visualization techniques. The nature of an x-ray is a projection of a 3D object onto a 2D screen. Thus, the actual scapholunate gap could be foreshortened, making the results misleading. Therefore, accuracy of measuring a gap on a 2D x-ray with the wrist positioned in neutral was questioned. In this study, three methodologies were developed to characterize the scapholunate gap. First, a ping-pong algorithm was developed and implemented to calculate the minimum distance between the carpal bones, scaphoid and lunate. Second, a four-point area method showed how a hand surgeon could pick four specific points, two on the scaphoid and two on the lunate, to represent the most important locations on the carpal bones that the hand surgeon would use to analyze the motion. Third, a solid volume was generated between the carpal bones by lofting between the cartilage areas of the bones.

Preliminary research showed the correlation between the volume and the minimum distance. The authors believe that the lofted volume can represent the ligament between the bones and be very valuable in the diagnosis of ligamentous injuries. Further research is needed to determine related applications. An add-in to SolidWorks, ORTHOPEDICS, was developed to implement all of the aforementioned scapholunate-gap calculation methods. Gap data can be collected automatically for all frames of a motion. The results of the gap data in this study showed that changes due to DIC or ST sectioned alone could not be detected. Furthermore, detection of major SL gap changes may be best detected in wrist ulnar deviation and flexion.

The methodology in the study can be applied to the analysis of any human or animal joint injury. Future study is needed to collect data from real patients, explore application fields, and develop stand-alone software.

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