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# The Hysteresis Effect in Carpal Kinematics

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## Abstract

**Purpose:** Carpal bones show hysteresis that is dependent on the direction of wrist motion during a continuous active loading protocol. We describe an accurate methodology for analyzing the hysteresis effect and we apply this model to analyze the effect of sequential ligament sectioning on scapholunate instability.

**Methods:** In 8 fresh cadaver forearms scaphoid, lunate, and third metacarpal motions were recorded while each wrist was moved in continuous cycles of active motion in flexion–extension and radioulnar deviation. Motions were analyzed for the intact state and after sequential sectioning of the scapholunate interosseous, scaphotrapezium, and radioscapho-capitate ligaments. Carpal motion was curve-fitted with respect to the third metacarpal motion using optimization criteria. The area between the 2 curves that represents opposite directions of wrist motion was measured to give the total hysteresis area. Repeated-measures analysis of variance was used to determine significance.

**Results:** In the flexion–extension trials the scaphoid and lunate total hysteresis area was significantly greater than the intact state only after all 3 ligaments were sectioned. In the radioulnar deviation trials the scaphoid total hysteresis area was significantly greater than the intact after just scapholunate interosseous ligament sectioning; however, the lunate total hysteresis area decreased with additional sequential sectionings in 4 of the 8 specimens as compared with the intact state. These 4 specimens started with a significantly greater intact total hysteresis area than the other 4 specimens.

**Conclusions:** The computation of the total hysteresis area from the hysteresis effect was found to be a sensitive technique to determine the subtle onset of abnormal carpal motion. By using this technique in a ligament sectioning study significant increases in the total hysteresis area were seen after just scapholunate interosseous ligament sectioning during wrist radioulnar deviation. This subtle change may signify the onset of dynamic scapholunate instability. The total hysteresis area of the lunate in a subset of lax specimens did not increase after ligament sectioning. This divergent behavior may explain why some patients with scapholunate instability do not develop dorsal intercalated segmental instability.

### Keywords

Carpal motion; hysteresis; neutral zone; scapholunate instability



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Normal and pathologic carpal motion has been studied since the late 19th century. Usually the wrist is injured experimentally to study various pathologic states. Researchers then use a variety of measurements to determine if and when a change in the carpal motion might be important.[1] Common techniques used for this analysis include comparing changes in carpal rotation angles[2,3] or changes in the helical axis.[4,5] One problem is that it often is difficult to decide if a statistically significant change in that particular measurement is clinically relevant. A significant change in a rotational angle or axis does not by itself necessarily represent a clinical pathologic state. In addition helical axis analysis in itself can be cumbersome to compute and difficult to understand and relate to clinical situations.

Webster defines hysteresis as “retardation of the effect, when the forces acting upon a body are changed.”[6] A hysteresis effect that is well known occurs during breathing, in which there is a difference in the pressure-volume curve between lung inflation and deflation.[7] Other biologic systems including cell membrane ion channels, DNA denaturation, and viscoelastic materials such as ligaments and tendons also show hysteresis.[8–15]

Long and Brown[16] showed that digital motion in the hand exhibits hysteresis. More recently Short et al[3,17,18] showed that carpal bones show a certain amount of hysteresis that is dependent on the direction of the wrist motion during a continuous active loading protocol. For example, the amount the scaphoid was flexed at a particular wrist position was different depending on the direction the wrist was moved to get to that position. The hysteresis was then the difference in the path of carpal motion. This effect was noticed for the 2 carpal bones studied, the scaphoid and lunate, for all planes of motion during both wrist radioulnar deviation and flexion–extension.

Recently researchers in spine biomechanics have equated the hysteresis effect during active motion protocols to the neutral zone.[19–21] The neutral zone, which also can be considered a region of joint laxity, has been described well for the spine and has been shown to be a more sensitive biomechanical parameter than range of motion in determining spinal instability.[22,23]

The purpose of this study was to describe a way to analyze the hysteresis effect that occurs in carpal motion. Our second purpose was to attempt to use this analysis to distinguish between normal and abnormal carpal kinematics. An increase in hysteresis may be an indicator of increased carpal instability. As a test case the effect of sequential sectioning of the scapholunate interosseous ligament (SLIL), scaphotrapezium (ST) ligament, and radioscapho-capitate (RSC) ligament on hysteresis was studied.

## Materials and Methods

Before describing the experimental protocol it is important to define a few terms. The neutral zone is the portion of physiologic motion that is produced with minimal load[24] (Fig. 1). Minimal load is a small load that is greater than 0 and just enough to move the joint and overcome gravity and friction. The neutral zone represents the biomechanical equivalent of the clinical concept of joint laxity. A very lax joint should have a larger neutral zone. The elastic zone is that portion of the range of motion, as shown in Figure 1, that is produced using sufficient physiologic loads.[24]

In this study a carpal bone may be flexing or extending as a consequence of multiple varying tendon loads used to move the wrist through an arc of motion. The specific motion of an individual carpal bone varies slightly depending on the direction in which the wrist is moved (Fig. 2). Here the difference between these motions is defined as the hysteresis area, which has been equated to the neutral zone. Thus the amount of hysteresis area should represent the degree

of laxity. For example, if enough intrinsic carpal ligaments have been injured then the carpus should have a larger neutral zone, be more lax, and thus have a larger hysteresis effect.

### Experimental Set-up

The experimental protocol, including the use of the wrist joint stimulator, has been described previously.[3,25] Briefly 8 fresh-frozen cadaveric arms amputated at the midhumerus level were dissected free of skin, muscles, and subcutaneous tissue. The wrist capsule and ligaments were left intact. All the extrinsic wrist tendons and the abductor pollicis longus tendon also were left intact to allow for the active wrist motion protocol. Each specimen was examined by radiocarpal and midcarpal arthroscopy and fluoroscopy. Any specimen with evidence of scapholunate instability or any other carpal instability, ligament tears, or degenerative arthritis was eliminated from the study. The average age of the cadavers was 71 ± 14 years; 5 were male. Carbon fiber rods were placed in the scaphoid, lunate, and radius. Motion sensors (Polhemus Fastrak; Polhemus Inc., Colchester, VT) then were attached to these rods and directly to the third metacarpal. These sensors allowed motion to be tracked relative to an electromagnetic source. Prior pilot studies performed in our laboratory have shown that the accuracy of this system in this environment is 0.2 mm and 0.2°.[3]

Active motion was provided by a wrist joint simulator in continuous arcs of wrist motion from 30° of extension to 50° of flexion and from 10° of radial deviation to 20° of ulnar deviation. The simulator allows reproducible cycles of motion by applying physiologic forces on the wrist flexor and extensor tendons. Each tendon is attached to a force transducer, which then is attached to a hydraulic cylinder. Software algorithms that are based partly on the position feedback from the third metacarpal sensor control the wrist motion.

The wrists were moved by the simulator cyclically for 6 consecutive cycles. Each cycle took 10 seconds to complete. The first 5 cycles were used to precondition the specimen. The sixth cycle was used for the motion analysis when comparing different ligament sectioning trials. In addition the fifth cycle was compared with the sixth cycle of the intact state to assess the reproducibility and validity of this methodology. Our belief was that the fifth and sixth cycles should be very similar to each other, and that if hysteresis is a real phenomenon in carpal motion then it also should be very similar between these 2 cycles.

Motion was measured and analyzed for the intact state and after each sequential sectioning of the SLIL, ST ligament, and RSC ligament. For the SLIL, the dorsal, palmar, and membranous portions of the ligament were sectioned through a radial midcarpal arthroscopy portal. In the case of the ST the ligament was identified and marked at the time of initial dissection and later cut under direct vision. For the RSC the ligament was identified arthroscopically at the time of dissection and tagged to allow sectioning during the experiment.

### Motion Analysis

The motion in each plane and in each direction was plotted with respect to the third metacarpal motion. A regression analysis was used to determine the best equation to describe the curves (Appendix; this appendix may be viewed at the *Journal*'s Web site, www.jhandsurg.org). The hysteresis area between the 2 curves of motion based on the direction of motion was computed using the rectangular method (Appendix). This area calculation was computed for the scaphoid and lunate in each plane of motion and theoretically is equivalent to the neutral zone. The computed hysteresis area for the 3 planes of motion was summed to determine the total hysteresis area of that carpal bone. We used 1-factor repeated-measures analysis of variance and a *post hoc* Duncan test to determine significance with an $\alpha$ value of 0.05.

## Results

The active wrist protocol resulted in reproducible motion. The data for the last ligament sectioning trials for 1 of the specimens was not included in the analysis because the carpal bone post was impinging on the radius. Figures 2 and 3 show an example of the hysteresis and hysteresis calculations from 1 of the specimens. The hysteresis area increased dramatically after just SLIL sectioning. We found that the total hysteresis area of the fifth preconditioning cycle of both the scaphoid and lunate (intact 1) was very similar to the total hysteresis area of the sixth cycle (intact 2) in the intact state. This was true for both the wrist flexion–extension and radioulnar deviation trials (Figs. 4, 5).

In the flexion–extension trials the scaphoid and lunate total hysteresis area was significantly greater than the intact total hysteresis area only after all 3 ligaments were sectioned (Fig. 4). In the radioulnar deviation trials the scaphoid total hysteresis area was significantly greater than the intact total hysteresis area after only SLIL sectioning (Fig. 5). Although the lunate total hysteresis area increased with sequential ligament sectioning, this increase was not significant compared with the intact state.

Knowing that the scaphoid and lunate predominately move in unison during radioulnar deviation, these conflicting total hysteresis area results for the radioulnar deviation trials were unexpected. We then looked carefully at the individual specimen lunate total hysteresis area data during wrist radioulnar deviation (Fig. 6). We found that in half of the specimens (subset A) the lunate total hysteresis area decreased rather than increased on sequential ligament sectioning. The same subset of specimens (subset A) had significantly greater intact total hysteresis area than the other 4 specimens (subset B) (58.2 degrees$^2$ vs 24.6 degrees$^2$).

Separate analysis of these subsets found that for the subset B specimens the lunate total hysteresis area was significantly greater than the intact total hysteresis area after only SLIL sectioning (Fig. 7). This was similar to the results for the scaphoid total hysteresis area during the wrist radioulnar deviation trials. For the subset A specimens the lunate total hysteresis area after all the ligaments were sectioned was decreased significantly compared with the intact state.

## Discussion

The purpose of this study was to describe a methodology that can be used to analyze the hysteresis effect that exists in carpal motion. By calculating the total absolute area between the 2 curves of motion the hysteresis area can be determined. We believe that the sum of the hysteresis areas in 3 planes of motion can be used to calculate the total hysteresis area and is useful in quantifying instability of the wrist. The total hysteresis area represents the overall degree of instability or laxity for a carpal bone.

We applied this model to a sequential sectioning protocol to determine scapholunate instability. We found significant increases in the scaphoid total hysteresis area after only SLIL sectioning during the wrist radioulnar deviation trials. The assumption was that the first evidence of a significant increase in total hysteresis area for any of the carpal bones during any wrist motion trials represents enough instability for it to be considered pathologic.

We found that the total hysteresis area was very similar between the fifth and sixth cycles. Simple preconditioning of the specimen did not by itself increase the total hysteresis area. These results support our view that hysteresis is a real, stable, and reproducible phenomenon of carpal motion. Ligament sectioning was required before significant changes in the total hysteresis area occurred.

There have been conflicting reports in the literature regarding which ligament(s) are required to produce scapholunate instability during sequential ligament sectionings. Linscheid et al[26] found that both the SLIL and RSC were required before subluxation of the scaphoid or scapholunate gap would occur. In contrast Blatt[27] found that only when the SLIL and dorsal intercarpal ligament insertions were severed would rotatory subluxation of the scaphoid occur. Both of these investigators found that if only the SLIL was sectioned the scapholunate gap would remain unchanged.

The problem with these studies is that the endpoint sought was frank static changes in the scaphoid rotation or the scapholunate gap. Sectioning the SLIL may result in some pathologic dynamic state but not in obvious static changes. Looking for radiographic changes may not be sensitive enough to detect any differences. We believe that changes in the hysteresis effect may be a more sensitive marker for detection of this type of subtle instability. Isolated SLIL injuries then may represent the pathophysiology behind dynamic scapholunate instability, in which there is no frank static radiographic scaphoid subluxation or scapholunate diastasis.

The concept that the wrist joint shows this hysteresis phenomenon during cyclic motion might be used to detect occult injuries clinically. Patients who have torn ligamentous structures initially may have normal x-ray findings and inconsistent physical examination results. This condition has been described by Watson et al[28] as dynamic or predynamic carpal instability. A delay in diagnosis of this condition may result in inferior clinical outcomes. The detection of large hysteresis areas that are seen in unstable wrists might be used as a diagnostic tool. Conceivably biplanar fluoroscopy can be performed on the injured wrist. The images obtained then can be processed by using a variety of software programs to evaluate the amount of hysteresis. Dennis et al[29] used *in vivo* videofluoroscopy and 3-dimensional image matching to quantify the position and orientation of knee implants. This technique may be suitable for *in vivo* studies of wrist instability. Those patients with a large hysteresis likely would have ligamentous disruption of the wrist. This would be a relatively inexpensive screening tool for acute soft-tissue ligament injuries.

Researchers in the past have shown that carpal bone motion may occur in 2 distinctly different patterns. Craigen and Stanley[30] found that the relative amount of scaphoid flexion–extension and radial/ulnar deviation varies in the population during wrist ulnar-to-radial deviation. Subsequently Garcia-Elias et al[31] showed that this variation can be correlated with the patient's laxity. They found that during wrist radial–ulnar deviation the scaphoid of very lax wrists moved dominantly in the sagittal plane (flexion–extension) whereas in the more rigid wrists the scaphoid moved preferentially in the frontal plane (radioulnar deviation).

In this study we also found 2 distinct patterns of lunate motion dependent on wrist laxity, specifically a subset of the specimens that had lunates with greater total hysteresis area in the intact state, implying that these specimens were more lax. These same specimens displayed a decrease in the total hysteresis area during ligament sectioning whereas the other subset showed a significant increase. The question is, why would the lunate of these lax specimens become less lax (show less hysteresis) with ligament sectioning?

One explanation may be that in lax wrists the dorsal/palmar stability of the lunate may be more dependent on the geometric bony architecture and less on the ligamentous attachments. Specifically, in the intact state the lunate shows a large hysteresis because the ligaments still are intact and result in lunate motion. As these ligament are sectioned, however, the lunate moves less instead of moving more. The lunate is possibly more secure and relatively immobile in the radiolunate fossa because of geometric stability while the rest of the carpal bones continue to show increasing hysteresis. This disparity may explain why some patients with an acute scapholunate injury show a dorsal intercalated segmental instability (DISI) pattern while others

do not. This does not mean that patients with laxity are more or less prone to injury but that these patients may not show a DISI pattern after suffering a severe scapholunate injury. This also could explain why SLIL reconstructions in some patients fail because these reconstructions tend not to do well in patients with a DISI deformity. These patients may have had a severe injury, be lax, and just not show a DISI deformity on plain radiographs.

Similar to all *in vitro* experiments our study has certain limitations. Our cadaveric model could not hope to account for the *in vivo* healing and adaptation that may occur after ligament injury. Although we had a small number of specimens we were able to find significance. Another limitation is related to the statistical significance of the changes in the total hysteresis area. Although we observed significant changes of the neutral zone in radioulnar deviation motions after the SLIL was sectioned, we did not see statistically significant changes in the flexion–extension motions until all 3 ligaments were sectioned; however, a substantial increase in the neutral zone was observed after sectioning just the SLIL. These results support the concept of varying levels of instability and need further investigation to determine the relationship between significant neutral zone changes and clinically relevant carpal instability.

Another limitation of the study was the limited variation of the ligaments chosen to section. Only the SLIL, ST, and RSC ligament combinations were tested. Additional ligaments or other combinations were not tested. Other ligaments that probably are important in scapholunate instability include the dorsal intercarpal ligament, dorsal radiocarpal ligament, and the scaphocapitate ligament.

We found that by using the total hysteresis area we were able to detect subtle scapholunate instability even after only SLIL sectioning. We believe that this type of analysis can be used in future studies as a powerful technique in distinguishing between normal and abnormal carpal motion.

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## Appendix

## Regression Analysis

Curves were created by plotting the motion of each of the carpal bones with respect to the third metacarpal motion. This was performed for each plane of motion and for each direction of motion. Regression analysis using 60 different equations was performed to determine the best type of model to fit these data. A curve fit was performed for each direction of each motion. Polynomials were found consistently to fit better.

Selecting the polynomial order is difficult. The higher the polynomial order of curve fit usually results is the better fit but also can result in a more complex model than may be necessary and may not be biologically plausible. A stepwise regression using the F test was performed to select the best polynomial order. The F test allows one to choose the smallest polynomial order without sacrificing accuracy. This test is depicted by the following equation,

$$F=\frac{(SS_1-SS_2)/(df_1-df_2)}{SS_2/df_2}, \quad \text{Equation 1}$$

where *SS* is the sum of squares, *df* is the number of degrees of freedom, subscript *1* refers to the model with fewer parameters, and subscript *2* refers to the model with more parameters.[32] This process consists of adding successive higher-order polynomials until an order term is found that does not significantly ($\alpha < 0.01$) improve the fit.[33]

## Rectangular Area Method Calculation

Once the polynomial equation was determined for each curve the area between the 2 curves for each direction of motion was computed. This hysteresis area was approximated using the rectangular method of calculating the area between 2 curves where

$$NZ=\sum_{a}^{b}|f_1(x)-f_2(x)|\Delta x,$$

Equation 2

where $f_1(x)$ and $f_2(x)$ are the 2 polynomial equations, $a$ and $b$ represents the range of wrist motion, and $\Delta x$ is the width of the rectangle.[34] In this study $\Delta x$ was set to 0.1°, which was clearly below the accuracy of the Polhemus system to ensure a good approximation. The area calculated with the second equation is the total absolute area between the 2 curves. In contrast a standard integral calculation of the area between the 2 curves could result in both negative and positive calculated subsection areas. This would occur if the 2 curves intersected each other. The integral calculation then would result in a smaller total area value. The total absolute area between the curves thus better represents the aggregate laxity of each of the carpal bones.

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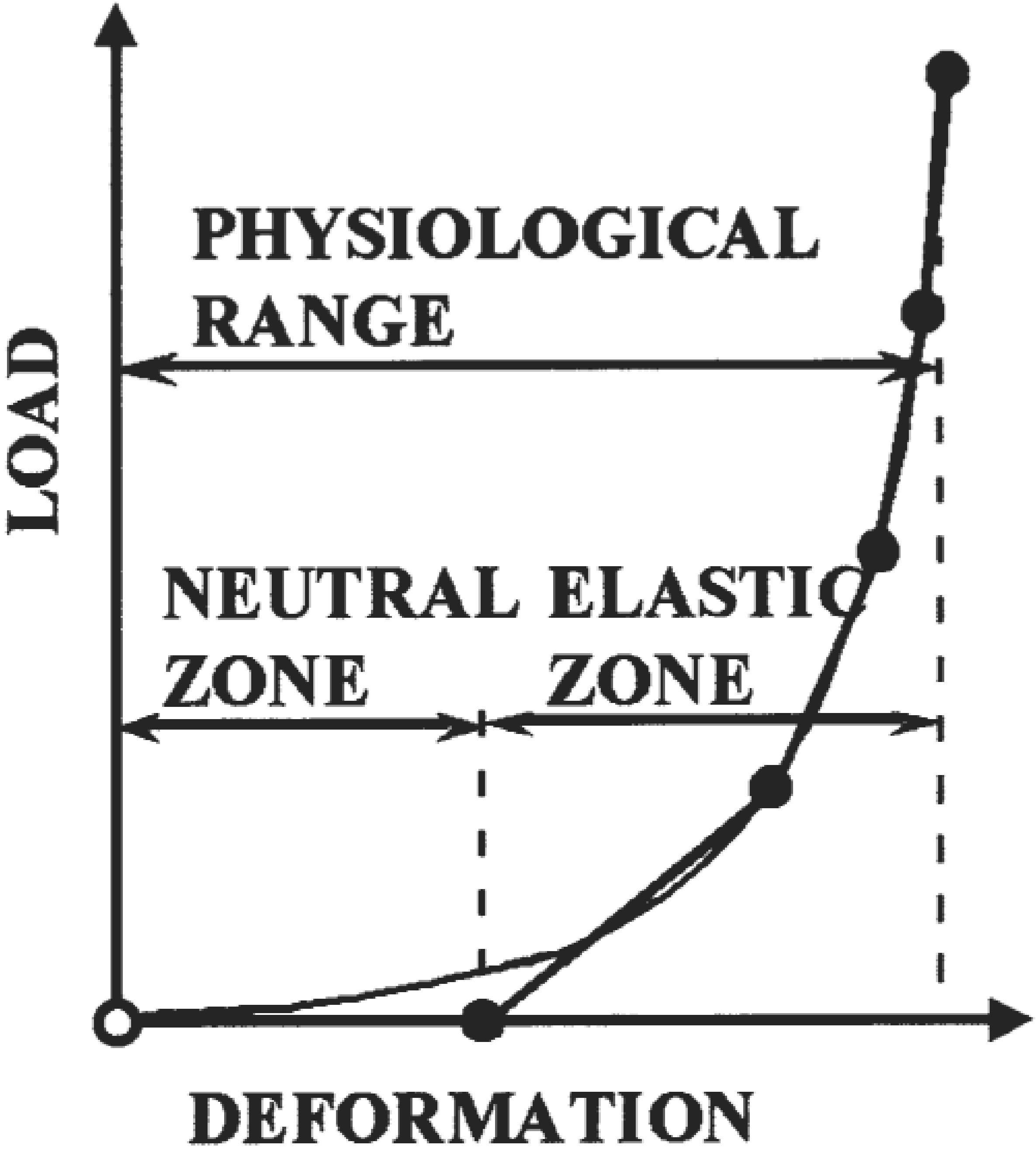


**Figure 1.**
Load-deformation curve. The neutral zone is the portion of the load-deformation curve where minimal load is required to produce deformation. The elastic zone is the portion of the load-deformation curve beyond the neutral zone until the end of the physiologic range of motion. Adapted from Panjabi.[24]

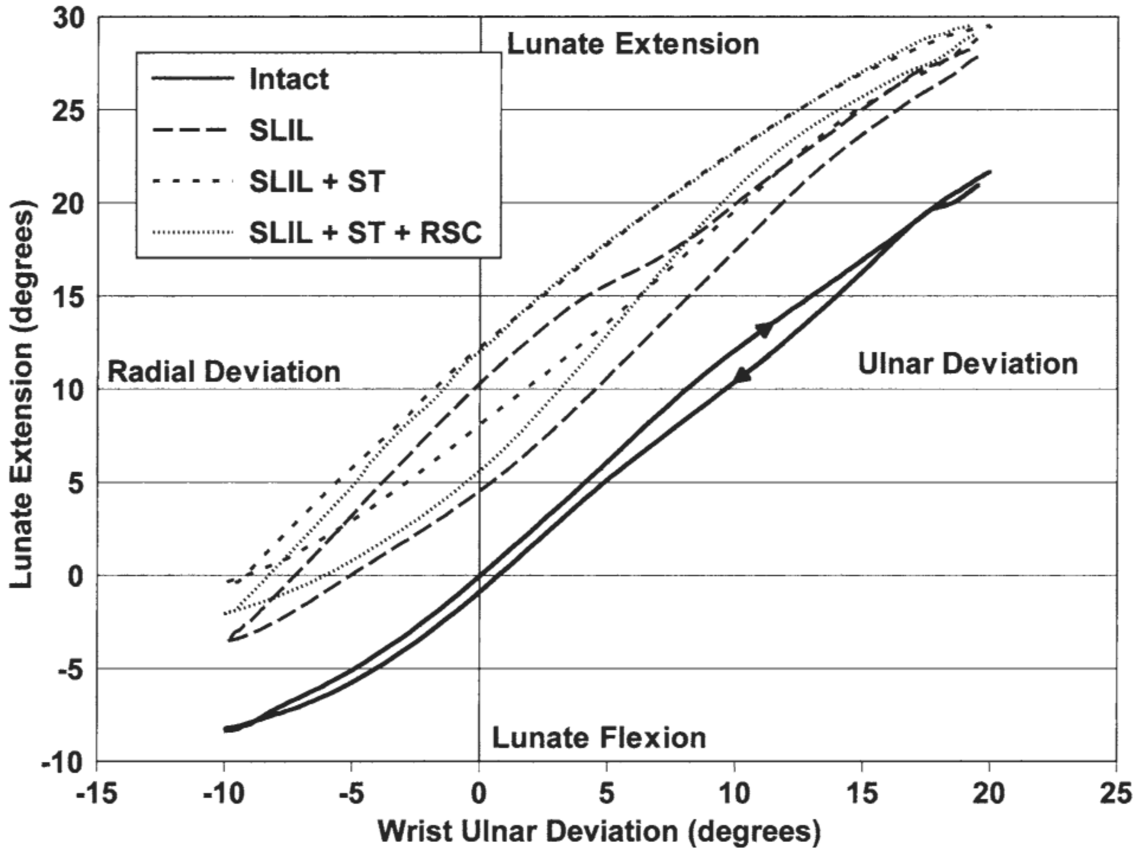


**Figure 2.**
Motion data for a single specimen. Motion of the lunate in the flexion–extension plane during wrist radioulnar deviation. The position of the lunate depends on the direction of the wrist motion, thus creating the hysteresis effect. This hysteresis increases during the sequential ligament sectioning trials.

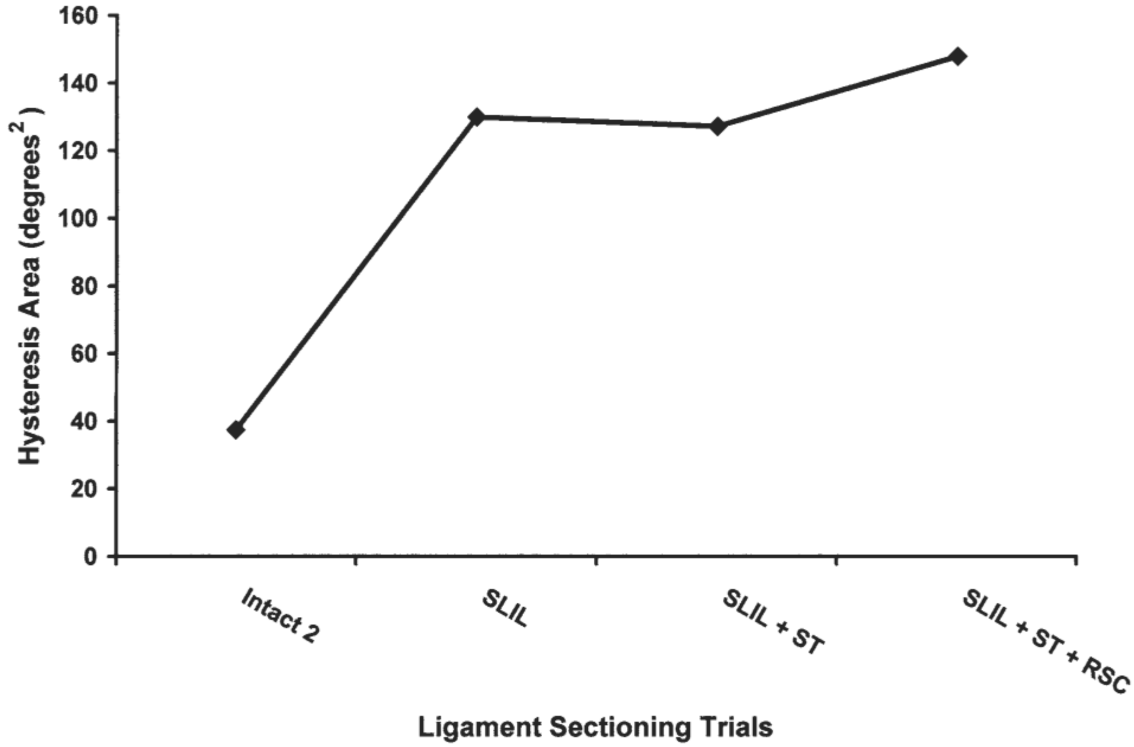


**Figure 3.**

Summary data for the single specimen data shown in Figure 2. Calculated hysteresis area for intact wrist and after each increment of ligamentous sectioning for the motions in Figure 2. There is a dramatic increase in the hysteresis area on the sectioning the SLIL.

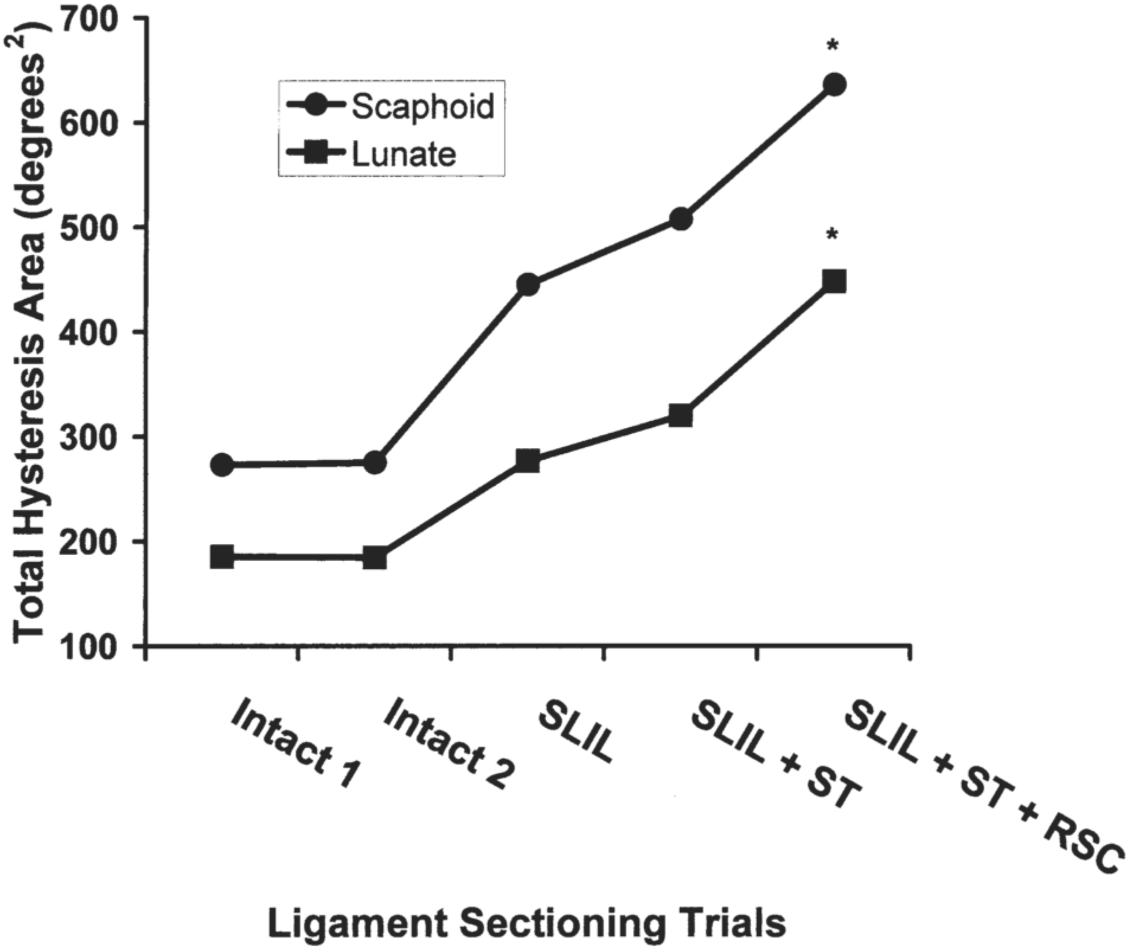


**Figure 4.**
Total hysteresis area for the wrist flexion–extension trials. The average total hysteresis area for the wrist flexion–extension trials for all 8 specimens. The total neutral zone is nearly identical between the fifth preconditioning cycle (intact 1) and the sixth cycle (intact 2) for the intact state. *Only after all the ligaments have been sectioned is the total hysteresis area significantly greater than the intact state (intact 2) for both the scaphoid and the lunate.

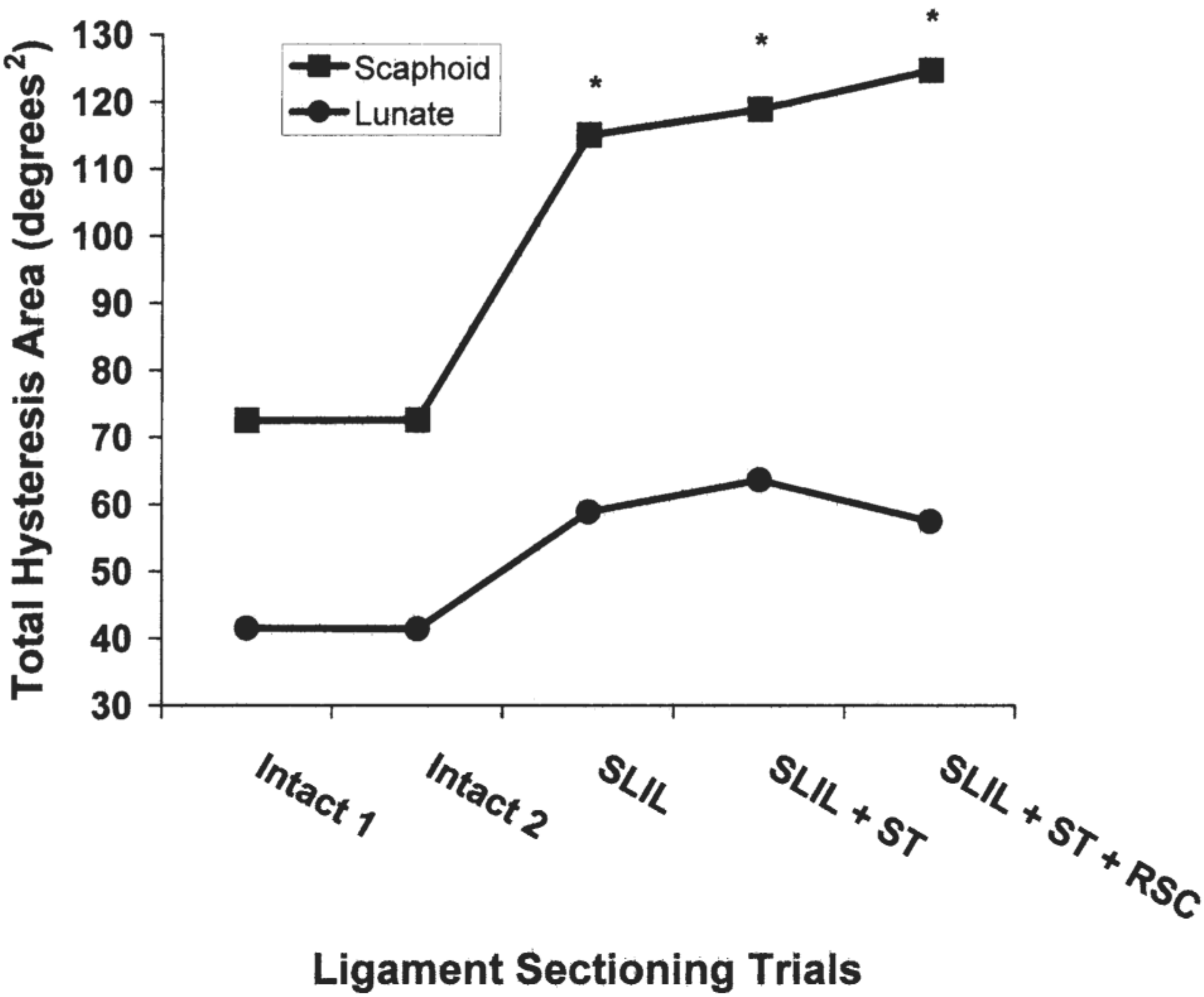


**Figure 5.**
Total neutral zone for the wrist radioulnar deviation trials. The average total hysteresis area for the wrist radioulnar deviation trials for all 8 specimens. Again there is minimal difference between the fifth and sixth cycles in the intact state (intact 1, intact 2). *The total hysteresis area of the scaphoid increases significantly after just the SLIL sectioning. Although the total hysteresis area of the lunate does increase after ligament sectioning, it is not statistically significant.

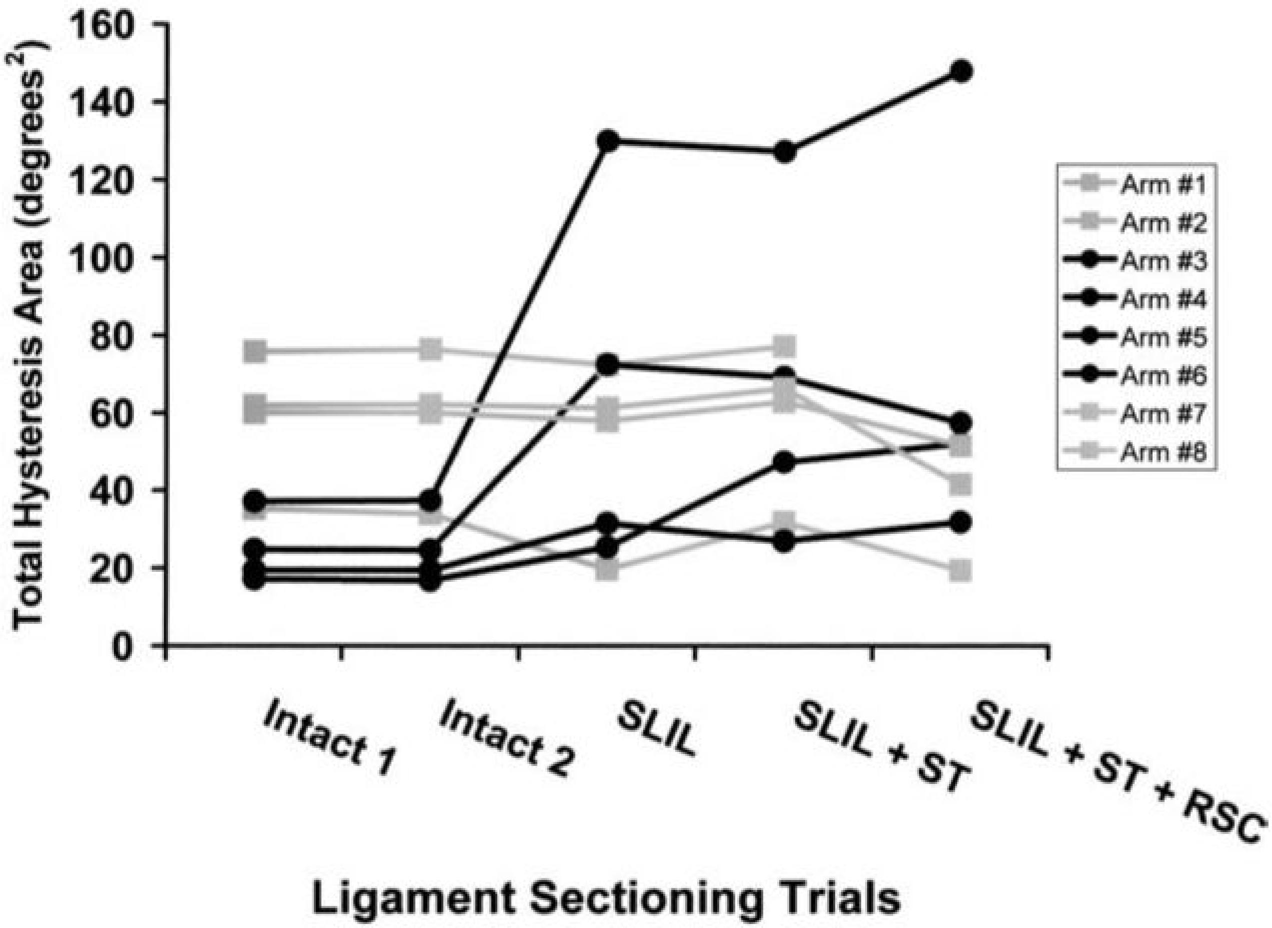


**Figure 6.**
Lunate total hysteresis area data for all specimens during wrist radioulnar deviation trials. A subset of the specimens (subset A) consisting of arms 1, 2, 7, and 8 not only had a leveling off or a decrease in the total hysteresis area on sequential ligament sectioning but also had an intact total hysteresis area that was significantly greater than the other specimens (subset B, arms 3, 4, 5, 6).

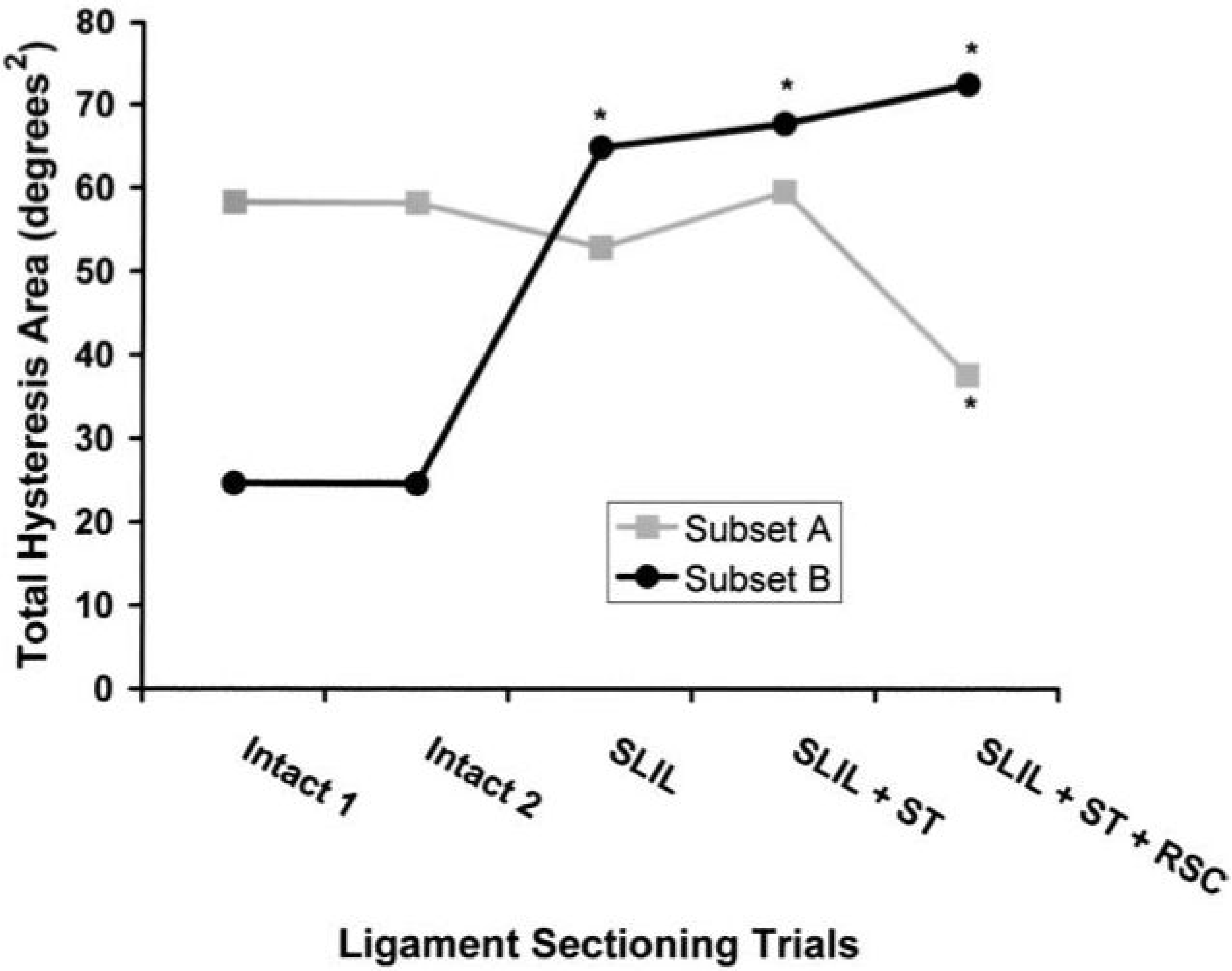


**Figure 7.**
Summary data for each subset during wrist radioulnar deviation. Lunate total hysteresis area during the wrist radioulnar deviation trials. For the subset B specimens the lunate total hysteresis area increases significantly (*) after SLIL sectioning. In contrast the lunate total hysteresis area after all the ligaments have been sectioned is significantly (*) decreased compared with the intact state for subset A specimens.