The Hysteresis Effect in Carpal Kinematics

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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 radioscaphocapitate 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. (J Hand Surg 2006;31A: 594.e1–594.e8. Copyright © 2006 by the American Society for Surgery of the Hand.)

Key words: 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.

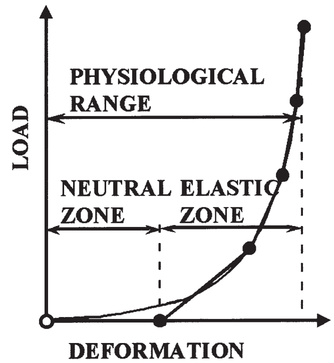

Figure 1. Load-deformation curve. The neutral zone is the portion of the load-deformation curve where minimal load is required to produce deformation. The elastic zone is the portion of the load-deformation curve beyond the neutral zone until the end of the physiologic range of motion. Adapted from Panjabi.[24]

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 radioscaphocapitate (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

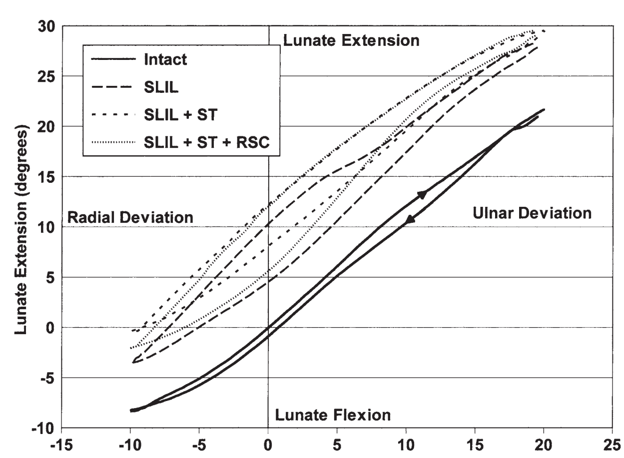

Figure 2. Motion data for a single specimen. Motion of the lunate in the flexion–extension plane during wrist radioulnar deviation. The position of the lunate depends on the direction of the wrist motion, thus creating the hysteresis effect. This hysteresis increases during the sequential ligament sectioning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