INTRODUCTION
The most common wrist ligament injury resulting from a fall on an outstretched hand involves a tear of the scapholunate interosseous ligament (SLIL). SLIL tears can be difficult to diagnose acutely with standard radiographs and may lead to progressive carpal collapse, degenerative joint disease, and wrist arthritis. The degree to which a complete tear of the SLIL affects carpal 20 kinematics (if at all) is hotly debated, and derived largely from biomechanical testing of cadaveric specimens. The recent ability to measure three-dimensional in vivo carpal kinematics has facilitated a non-invasive precision analysis of carpal kinematics. Kinematic analysis based on markerless bone surface registration (MBR) is a potentially valuable tool for in vivo studies and clinical use, as it can accurately track skeletal motion in complex joints [1,2]. The aim of this study was to test the hypothesis that SLIL tears alter in vivo carpal bone kinematics. The three-dimensional (3-D) kinematics of the carpal bones were measured using a noninvasive CT-based method [2]. The kinematics of the injured (Injured), as well as the uninjured contralateral wrist (Uninjured), were compared to an existing database of healthy male and female volunteers (Normals) in order to test our hypothesis.

METHODS
Using computed tomography (CT)-based MBR, carpal bone postures and kinematics were determined for both wrists (Injured and Uninjured) of eight subjects with arthroscopically-verified unilateral traumatic SLIL tears (7 males, 1 female, avg. age: 38 [range: 20-54]). These values were compared to data from healthy wrists of ten volunteers (n = 20) defined as Normal (5 male, 5 female, avg. age: 26 [range: 21-47]). After IRB approval and informed consent, both wrists were scanned simultaneously (voxel size: (0.2 to 0.9) x 1 mm) in positions of neutral, 30º and 60º of flexion (+), 30º and 60º of extension, and 20º of radial deviation. The surfaces of all carpal bones, radius and ulna were segmented and reconstructed from the CT volume images. Left wrists were mathematically reflected into right wrists to simplify analyses. Bone postures and kinematics were calculated with respect to the neutral position and described within an orthogonal coordinate system imbedded in the distal radius. The posture and kinematic analysis focused on the capitate, scaphoid and lunate bones. Carpal bone posture was described using the first principal axis of inertia of each carpal bone relative to the distal radial coordinate system. Carpal bone kinematics were described using helical axis of motion (HAM) variables, consisting of a rotation about and translation along a unique axis in 3D space, with respect to the distal radial coordinate system. Bone rotations were plotted as a function of capitale rotation and fit with linear regression lines to quantify the contribution of carpal rotation to wrist flexion and extension. Capitate rotation was used as a measure of wrist deviation.

The significance of the differences, if any, between the Injured (n = 8), Uninjured (n = 8), and Normal (n = 20) were examined for neutral posture and wrist flexion and extension. A one-way ANOVA and with Dunnett multiple comparison post-hoc test (p < 0.05) was used to determine if SLIL tears significantly altered carpal bone posture in the neutral wrist position. Student's t-tests with a Bonferroni correction factor for multiple comparisons (p < 0.017) were used to determine if the slopes of the linear regression lines describing carpal bone rotation differed.

RESULTS
The neutral posture of the lunate was significantly (p < 0.01) more extended in the Injured wrists (56 ± 13º) than in the Normal wrists (83 ± 8º). Surprisingly, but consistent with our other findings, the contralateral Uninjured lunate (53 ± 7º) was also significantly different from Normals, yet did not differ from the Injured. The Injured (24 ± 16º) and the Uninjured (27 ± 20º) scaphoids were not different, but both were significantly (p < 0.01) more extended than the Normals (49 ± 11º). Aligning the dorsum of the third metacarpal with the dorsum of the forearm to define the neutral wrist position was not precise, but the neutral postures of the capitate bones did not differ in the Injured (<50 ± 19º), Uninjured (<46 ± 23º), and Normal wrists (<45 ± 9º).

During wrist extension, the Injured and Uninjured lunates rotated 35% and 26% as much as the capitate, respectively, each rotating significantly less (p < 0.001) than the Normal lunate, which rotated 69% as much as the capitate. Extension of the lunate in the Injured and Uninjured wrists were not different (p = 0.77). During wrist flexion, the Injured and Uninjured scaphoids rotated 80% and 89% as much as the capitate, respectively, each rotating significantly more (p < 0.01) than the Normal scaphoid, which rotated 73% as much as the capitate. Flexion of the scaphoid in the Injured and Uninjured wrists were also not different from each other (p = 0.53).

DISCUSSION
Our results support the hypothesis that SLIL tears alter carpal bone kinematics. However, in the group of eight patients we studied, their asymptomatic, uninjured contralateral wrist was also found to have abnormal carpal bone kinematics. These results were based upon in vivo measurements made using a novel markerless CT-based methodology whose accuracy has been examined in vivo to be better than 2 degrees and 2 mm for the scaphoid, lunate and capitate. This method utilizes CT scans of the wrist in multiple static positions, so the kinematics are calculated between static postures. It is not known whether an actual dynamic method would yield similar findings.

There are previous reports that lend support to our findings. Other authors have demonstrated bilateral soft tissue defects after unilateral wrist injury in 60-100% of their patients [3,4]. In patients with a range of soft and hard tissue injuries, Feipel and Ruzoe [5] found that there were no significant kinematic differences between the injured and the contralateral, asymptomatic wrist, but there was a significant difference between both wrists of the injured patients and the wrists of that study’s uninjured volunteers. This finding is in direct agreement with ours. These authors found individual variations in normal carpal bone motion, which is in contrast to our finding of minimal kinematic variability between normal wrists. Their finding of normal variation might be attributed to their motion tracking algorithm which has a lower accuracy than our algorithm.

The findings of the current study do not explain why carpal kinematics are abnormal in both wrists of patients with unilateral SLIL tears. The effect of age on carpal kinematics is not known, but the fact that our injured cohort was, on average, twelve years older than the healthy volunteer group may be a factor. Unilateral injury may also result in a complex neuromuscular response factor. Unilateral ligament injury may also result in a complex neuromuscular response that affects carpal mechanics in both limbs. It may also be possible that there is no significant population of individuals predisposed to ligament injury due to abnormal carpal kinematics. Why there were none of these individuals in our healthy volunteer group is not clear. Further research is needed to confirm and understand the finding of bilateral abnormal carpal bone posture and kinematics in subjects with unilateral wrist ligament injuries.

REFERENCES

ACKNOWLEDGEMENTS
We thank C. Cobb & W. Smith for their assistance in acquiring the CT images.

*Department of Orthopaedics, Yale University, New Haven, Connecticut.

**Department of Orthopaedics, Brown University, Providence, Rhode Island. Orthopaedic Research, SWP-3, Rhode Island Hospital, 593 Eddy Street, Providence, RI 02903, 401-444-4231, Fax: 401-444-4559, joseph_crisco@brown.edu