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Original Research

Radiographic Evaluation of Carpal Mechanics and the Scapholunate Angle in a Clenched Fist with Dynamic Computed Tomography Imaging

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A R T I C L E I N F O

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Purpose: The long-term consequences of injuries to the scapholunate joint can severely limit hand function, and the potential for posttraumatic deformity makes early recognition of these injuries important. The purpose of this study was to evaluate the motion of the scapholunate joint in normal wrists through the radial and ulnar deviation using novel dynamic computed tomography (CT) imaging.
Methods: Fifteen participants consented to have their uninjured wrists scanned. A protocol was designed to ensure adequate time, yet limited exposure, for volunteers. Participants began with the hand in a relaxed fist position and then proceeded to clench the hand in a full fist and relax. Once relaxed again, the wrist was maximally ulnarly deviated and then maximally radially deviated in a fluid motion. Dynamic CT imaging was captured throughout the range of motion.
Results: The scapholunate angle was measured on dynamic wrist images. The mean range of the scapholunate angle that the wrists moved through was 37.2°–45.9°, and the mean midpoint angle was 41.2° ± 0.4°. All wrists had small, measurable differences in the scapholunate angle when moving from the maximum ulnar deviation to the maximal radial deviation. The average maximum angle change through the range is 11.7°, whereas the average minimum angle change was 0.9°.
Conclusions: In this study, scapholunate angle calculations using dynamic wrist CT scans were within the range of accepted normal for the angle in uninjured wrists. With the increased focus on dynamic imaging for wrist motion, it may be possible to derive a standardized protocol for mapping the carpal motion that is clinically applicable and reproducible.
Type of study/level of evidence: Diagnostic IV.

The scapholunate (SL) joint is one of the most studied aspects of the human wrist, given its clinical implications when an injury occurs. The long-term consequences of injuries to the SL joint and associated soft tissues can be debilitating and severely limit hand function and quality of life.[1–3] Scapholunate interosseous ligament (SLIL) injuries are the most common cause of wrist instability. If unrecognized, there is a high potential for posttraumatic deformity and osteoarthritic changes to other carpal joints.[4–6] Early detection of SLIL injuries can enable early intervention and possibly prevent the detrimental sequelae of a missed injury.[7]

The interaction of bones in the human carpus is complex, and therefore, the detection of an injury can be difficult. Current noninvasive work-up for diagnosing an SLIL tear includes static and stress radiographs, magnetic resonance imaging, and/or computed tomography (CT) arthrography. The typical evaluation of an injury is based on SL dissociation and angular changes in the bony relationships on imaging.[8–10] The human carpus is complex because of the interactions of bones and ligaments through several planes of motion.[11,12] Often, injury to the SLIL may only be visible on clenched

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fist views where the joint is loaded. It may take months for changes to become evident on static x-rays.[13] Advances in imaging from specific radiographs to CT and magnetic resonance imaging have allowed for a better understanding of wrist kinematics that may improve the diagnostic accuracy of wrist ligament pathology.[3,14–18] Advanced imaging often gives information regarding ligament structural integrity but not ligament sufficiency, which is problematic in cases of partial ligament tears.[5,13,19] Magnetic resonance imaging also provides excellent characterization of the ligamentous structures within the carpus but lacks an analysis of wrist kinematics.[20] Dynamic CT studies on wrist kinematics and the SL joint have primarily focused on the movement described as "dart throwers motion" and have lacked the imaging of carpal motion through the ulnar and radial deviation. [21,22] Dynamic CT allows a kinematic assessment of active wrist motion depicting slight positional changes with high temporal and spatial resolution. This advanced imaging has shown potential in evaluating carpal instability.[16,21,23–25]

The purpose of this study was to evaluate the technical feasibility of dynamic CT imaging to analyze the motion of the SL joint in normal wrists with a clenched fist through the radial and ulnar deviation. Our goal was to establish a protocol for the measurement of the normal joint on a novel dynamic CT wrist scan.[26] Understanding the appearance of a normal scan would be crucial to interpreting the imaging of an injured wrist using this new test.

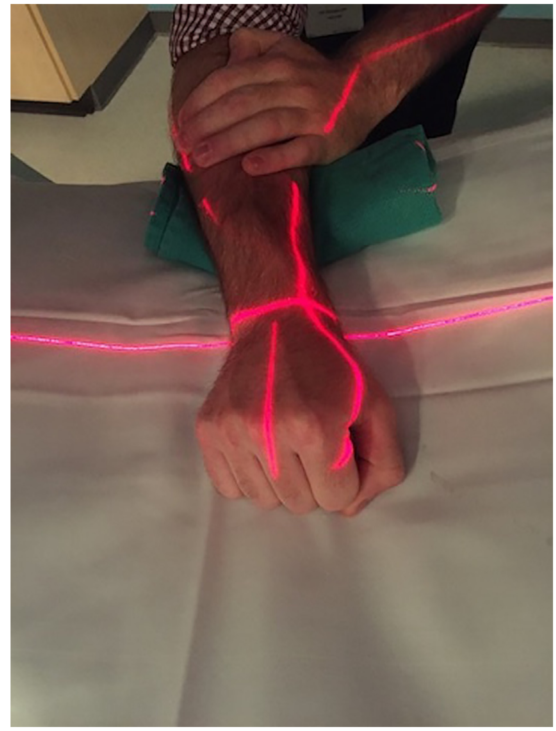

Figure 1. Participant wrist positioning in the CT scanned.

Materials and Methods

Population

Our prospective study obtained research ethics approval from our institution before the commencement (*HREB#2018.073*). Written informed consent was obtained from all individual participants, and the authors had full control of the data and images analyzed.[26]

Fifteen volunteers consented to have one of their wrists scanned. The wrist to be scanned was randomly selected with the flip of a coin. Eight participants were randomized to have the right wrist scanned and 7 to the left wrist. All participants denied any previous trauma to the wrist being scanned. Participants were excluded if they had any previous wrist surgery, cast immobilization, or symptoms of instability. Instability was defined as having pain, clicking, or popping in the wrist to be scanned. All 15 volunteers met the inclusion criteria and had their selected wrist scanned.

Four-dimensional CT image acquisition

The images were acquired using 320 Multidetector CT Scanner (Aquilion ONE ViSION Edition, software version 7.0; Toshiba Medical Systems Inc). All participants followed the identical sequence of movements while in the 4-dimensional (4D) CT scanner. This protocol ensured adequate time (10 seconds) for image acquisition yet limited radiation exposure. The protocol was developed on the CT scanner computer to ensure that the settings were the same for each participant. All participants underwent a training session with the investigator before image acquisition to ensure that they were familiar with the wrist motion protocol.

All scans were completed without complications.

Participants were provided with appropriate protective equipment and were positioned at the back of the gantry. The selected wrist was then placed on the table, palmar side down. The area to be scanned was set at 8 cm to include the distal radioulnar joint and the entire carpus. The radiocarpal joint was elevated with a folded towel to the level of the image acquisition sector to avoid wrist extension with clenching of the fist.[2] The forearm was rested on the imaging table, and the contralateral hand was used to steady the arm to prevent pronation, supination, or position changes through the elbow joint (Fig. 1).[26] Participants were asked to move their hand continuously from a relaxed fist position to a clenched fist and back to a relaxed fist. Once relaxed, the wrist was maximally ulnar deviated and then maximally radially deviated. All participants could complete the range of motion in the allotted 10-second interval delineated by the protocol.

Image analysis and postprocessing of wrist 4D CT studies

The images were acquired using the 320 Multidetector CT Scanner (Aquilion ONE ViSION Edition, software version 7.0; Toshiba Medical Systems Inc). Four-dimensional CT analysis was performed using an independent postprocessing workstation (Vitrea, Vital Images, Inc; Toshiba Medical Sytems) by using the 4D Ortho application. Measurements were collected by an orthopedic surgery resident (A.M.).

All volumes of the 4D CT images were analyzed to select the points used in the SL angle. The investigator manually placed one line tangential to the proximal and distal convexities of the scaphoid's palmar aspect. Once this segment was found to be adequately aligned on the scaphoid, the investigator scrolled through all acquisition volumes and found the frame that depicted the lunate in the profile. A line was drawn from the most distal palmar point of the lunate to the most distal dorsal point. A second line was drawn vertically through the line perpendicular to the first. Once an exact 90° angle was obtained in placing the second line, the first line through the lunate was deleted.[27]

After the markers of each angle were validated, the software automatically plotted the selected angle markers through all image positions collected for each wrist. The software calculated and plotted the angle measurements through each image obtained over the 10-second protocol interval (Fig. 2). We marked 3 angle measurements for each wrist scan. We found the average angle

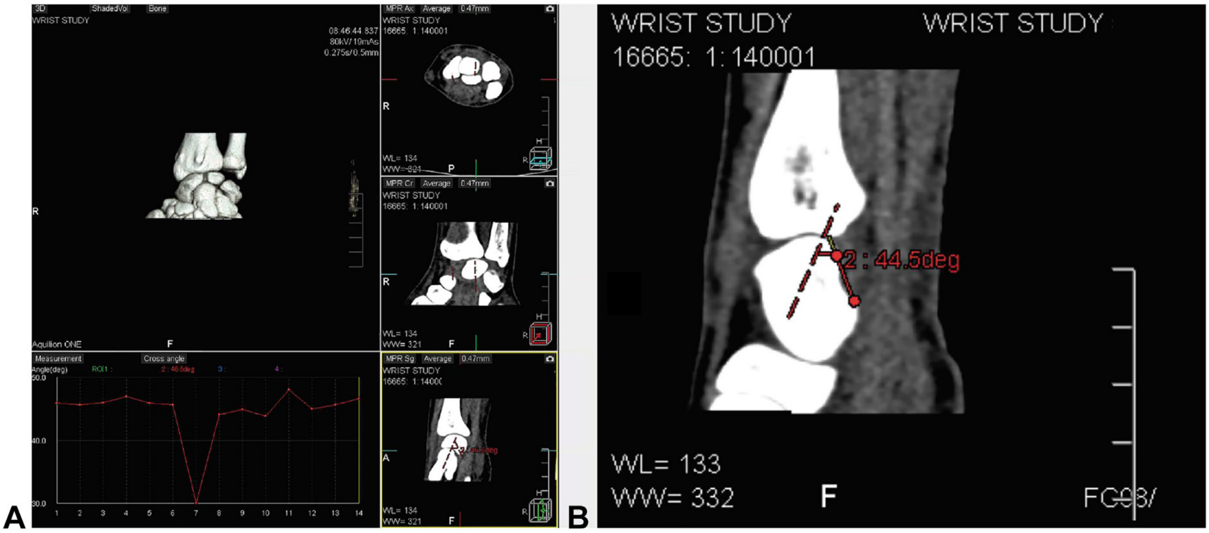

Figure 2. **A** 4D Orthopedic Analysis application (Toshiba Medical Systems Inc) analysis of the SL angle in a study volunteer. The image depicts 3D, axial, coronal, and sagittal dynamic CT with graphed SL angle measurements. Some measured lines are present on depicted slices, and **B** sagittal cut depicting the location of markers and measurement lines of the SL angle.

measurements for each participant. This was done to increase the validity of the angle being measured for each scan by reducing the measurement error for the angles. We plotted the 3 selected markers in all wrist scans through all directions of motion. We found the mean range and mean midpoint angle with SDs of the 3 measurement sets for all scans. The collective mean range and mean midpoint angle for all participants and images with SDs were then calculated.

Finally, we found the difference in angle size between the maximal ulnar deviation and the maximal radial deviation of each wrist in all 3 data sets. The average maximum and minimum angle changes through the range of motion were then calculated for all wrist scans.

Results

The movement in the healthy SL joint through a clenched fist and the radial and ulnar deviation is minimal. In our sample of normal wrists, there was minimal change in flexion and extension of the scaphoid and lunate, respectively. In a normal wrist on plain radiographs, the SL angle is between 30° and 70°. Measurements outside this range are suggestive of a ligament injury. The SL angle was measured on the images of all 15 participants and then tracked through the range of motion described in the protocol. Two wrist scans were excluded from the analysis because of the inability to track the SL angle through the full range of motion protocol. The mean range of the SL angle was calculated as 37.2°–45.9°, and the mean midpoint angle for each scan was 41.2° ± 0.4°. All wrists had small but measurable differences in the SL angle when moving from the maximum ulnar to the maximal radial deviation. The average maximum angle change through the range is 11.7°, whereas the average minimum angle change was 0.9°.

Discussion

The wrist contains complex sets of articulations, including the well-studied SL joint. Scapholunate interosseous ligament ruptures are the most common ligament injuries in the wrist.[8] This ligament is among the intrinsic ligaments that provide stability to the carpus, and its rupture can result in the collapse of the carpal scaffold. This injury can dramatically limit hand strength and function through instability.[28,29] Injury through the joint can progress to a dorsal intercalated segmental instability deformity that can lead to an advanced scapholunate collapse wrist. The malposition of the scaphoid (flexed) and lunate (extended) in a scapholunate collapse wrist leads to these progressive degenerative changes.[29] Early recognition and treatment of SLIL rupture may prevent late-stage wrist arthritis.

Measuring the SL angle and gap on static radiographs is the primary evaluation method for a SL dissociation injury. A gap of >3 mm and an angle of >70° is indicative of an SLIL tear. Kelly et al[26] previously evaluated the scans of this cohort and found that the SL gap widened minimally through a range of motion in normal wrists. In this analysis, we used the same cohort of normal wrists to evaluate SL angle.

A study by Megerle et al demonstrated that the SL gap was a more sensitive testing parameter for ligament injury, whereas the SL angle was a more specific parameter.[30] Of all radiographic measurements analyzed in the study, the SL angle had the highest specificity (0.93).[30] In addition, the angle size correlated with the SLIL tear severity. Another study in 2007 evaluated the diagnostic accuracy of plain radiographs by comparing the diagnosis of an SLIL tear by an SL gap and SL angle to the presence of a tear on wrist arthroscopy. They found that the specificity of the SL angle in the diagnosis of a SLIL injury was 85%.[8] In a logistic regression model analyzed in the same cohort, the SL angle was found to aid independently in the diagnosis of a ligament injury on plain radiographs. Both, pathologic SL gap and SL angle on plain radiographs are the best independent predictors of true ligament injury.[8]

Despite a strong correlation between radiographic parameters and wrist pathology, the diagnosis of SLIL tears is still difficult. Scapholunate interosseous ligament injuries are a spectrum of diseases, which makes diagnosing the pathology problematic. Partial rupture can take weeks to months to show malalignment on plain film.[30] Full-thickness tears may display static instability, which is evident on plain radiographs. However, less severe tears, as per the Watson and Ballet[29] classification, can be difficult to detect. Magnetic resonance imaging improves anatomic evaluation of wrist ligaments and subtle tears but lacks assessment of the functional integrity of the structures.[22] Diagnostic arthroscopy of the wrist is the current gold standard for diagnosing static and dynamic wrist pathology. However, this is an invasive measure that could be avoided with assessment via dynamic CT.[31]

Static imaging of the wrist has been the mainstay in diagnosing ligament injuries, and image quality has improved over time. Despite this, dynamic instability injuries remain a diagnostic challenge. Classification systems have been established for SL dissociation: the European Wrist Arthroscopy Society and Geissler classifications. These are meant for use during arthroscopy, and plain radiographs have a poor correlation with the diagnosis of dynamic instability using these staging methods.[32,33] Motion analysis imaging allows for the visualization of slight positional changes in the relationship of the carpals during motion.[25] This study examines the motion through clenching of the fist and radial and ulnar deviation, as opposed to the dart throwers motion, which has been more widely studied in 4D CT. This may help to understand better the normal kinematics of the carpals in several planes of motion. Dynamic CT may eventually be used as an advanced imaging modality for preoperative planning in wrists with known SLIL pathology. Understanding normal imaging anatomy is imperative before using this dynamic CT for defining pathology.

We have shown that dynamic CT is a user-friendly means of imaging the motions of the SL joint. This study shows that the setup for 4D CT is feasible in a clinical setting. The risk to the patient through radiation exposure is low because of the minimal time to complete the image acquisition. This dynamic CT could provide a noninvasive means of identifying the early stages of injury without subjecting patients to arthroscopy.

The potential for posttraumatic deformity to other carpal joints makes early recognition of these injuries important. Functional impairment from the sequelae of ligament injury can potentially be circumvented by early repair. Primary repair of the ligament is superior to delayed repair because the healing potential of the ligament decreases with time.[34] Even with an established diagnosis, surgical repair or reconstruction techniques are challenging and often do not have reliable outcomes for the patient.[1,35]

The limitations in dynamic CT studies include that the images are an approximation based on tomographic image data.[34] The landmarks used to measure the angles were selected manually and subject to measurement error. The already small sample size was reduced to 13 scans when 2 of the wrist images were excluded. In these 2 scans, the SL angles were unable to be accurately mapped through the entire range of motion. The assumption of participants' wrists being normal was based on their self-reported lack of pain or history of injury and did not rule out underlying abnormalities. In addition, specific software is required for capturing and processing the images, which is not available at all clinical sites. A larger study would be required to characterize the normal joint motion fully. Further 4D CT studies will need to be performed, including patients with documented or suspected SL instability, to assess whether these measurements are accurate ways of characterizing SL joint stability.

In conclusion. dynamic CT assessments of musculoskeletal patients is a rapidly evolving field that aims to balance improved diagnostic techniques while reducing risk to patients. With increased focus on dynamic imaging for wrist motion, it may be possible to derive a standardized protocol for mapping the SC angle that is both user-friendly and reproducible.

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References

1. Garcia-Elias M, Lluch AL, Stanley JK. Three-Ligament tenodesis for the treatment of scapholunate dissociation: indications and surgical technique. *J Hand Surg Am*. 2006;31(1):125–134.
2. Gilula LA. Commentary: the clenched pencil view. *J Hand Surg Am*. 2003;28(3): 419–420.
3. Tay SC, Primak AN, Fletcher JG, et al. Four-dimensional computed tomographic imaging in the wrist: proof of feasibility in a cadaveric model. *Skeletal Radiol*. 2007;36(12):1163–1169.
4. Dobyns JH, Linscheid RL, Macksoud WS. Proximal carpal row instability nondissociative. *Orthop Trans*. 1995;9:574.
5. Kitay A, Wolfe SW. Scapholunate instability: current concepts in diagnosis and management. *J Hand Surg Am*. 2012;37(10):2175–2196.
6. Kuo CE, Wolfe SW. Scapholunate instability: current concepts in diagnosis and management. *J Hand Surg Am*. 2008;33(6):998–1013.
7. Kakar S, Breighner RE, Leng S, et al. The role of dynamic (4D) CT in the detection of scapholunate ligament injury. *J Wrist Surgery*. 2016;5:306–310.
8. Pliefke J, Stengel D, Rademacher G, Mutze S, Ekkernkamp A, Eisenschenk A. Diagnostic accuracy of plain radiographs and cineradiography in diagnosing traumatic scapholunate dissociation. *Skeletal Radiol*. 2008;37(2):139–145.
9. Kwon BC, Baek GH. Fluoroscopic diagnosis of scapholunate interosseous ligament injuries in distal radius fractures. *Clin Orthop Relat Res*. 2008;466(4): 969–976.
10. Schimmerl-Metz SM, Metz VM, Totterman SM, Mann FA, Gilula LA. Radiologic measurement of the scapholunate joint: implications of biologic variation in scapholunate joint morphology. *J Hand Surg Am*. 1999;24(6):1237–1244.
11. Berger RA. The gross and histologic anatomy of the scapholunate interosseous ligament. *J Hand Surg Am*. 1996;21(2):170–178.
12. Rajan PV, Day CS. Scapholunate interosseous ligament anatomy and biomechanics. *J Hand Surg Am*. 2015;40(8):1692–1702.
13. Linscheid RL, Dobyns JH, Beabout JW, Bryan RS. Traumatic instability of the wrist: diagnosis, classification, and pathomechanics. *J Bone Joint Surg Am*. 2002;84(1):142.
14. Alta TD, Bell SN, Troupis JM, Coghlan JA, Miller D. The new 4-dimensional computed tomographic scanner allows dynamic visualization and measurement of normal acromio- clavicular joint motion in an unloaded and loaded condition. *J Comput Assist Tomogr*. 2012;26(6):749–754.
15. Halpenny D, Courtney K, Torreggiani WC. Dynamic four-dimensional 320 section CT and carpal bone injury-a description of a novel technique to diagnose scapholunate instability. *Clin Radiol*. 2012;67(2):185–187.
16. Leng S, Zhao K, Qu M, An KN, Berger R, McCollough CH. Dynamic CT technique for assessment of wrist joint instabilities. *Med Phys*. 2011;38(suppl 1):S50.
17. Ramamurthy NK, Chojnowski AJ, Toms AP. Imaging in carpal instability. *J Hand Surg Eur Vol*. 2016;41(1):22–34.
18. Shores JT, Demehri S, Chhabra A. Kinematic "4 dimensional" CT imaging in the assessment of wrist biomechanics before and after surgical repair. *Eplasty*. 2013;13:e9.
19. Bille B, Harley B, Cohen H. A comparison of CT arthrography of the wrist to findings during wrist arthroscopy. *J Hand Surg Am*. 2007;32(6):834–841.
20. Bateni CP, Bartolotta RJ, Richardson ML, Mulcahy H, Allan CH. Imaging key wrist ligaments: what the surgeon needs the radiologist to know. *AJR Am J Roentgenol*. 2013;200(5):1089–1095.
21. Edirisinghe Y, Troupis JM, Patel M, Smith J, Crossett M. Dynamic motion analysis of dart throwers motion visualized through computerized tomography and calculation of the axis of rotation. *J Hand Surg Eur Vol*. 2014;39(4): 364–372.
22. Garcia-Elias M, Alomar Serrallach X, Monill Serra J. Dart- throwing motion in patients with scapholunate instability: a dynamic four-dimensional computed tomography study. *J Hand Surg Eur Vol*. 2014;39(4):346–352.
23. Gondim Teixeira PA, Formery AS, Hossu G, et al. Evidence-basedrecommendations for musculoskeletal kinematic 4D-CT studies using wide area-detector scanners: a phantom study with cadaveric correlation. *Eur Radiol*. 2007;27(2):437–446.
24. Demehri S, Hafezi-Nejad N, Morelli JN, et al. Scapholunate kinematics of asymptomatic wrists in comparison with symptomatic contralateral wrists using four-dimensional CT examinations: initial clinical experience. *Skeletal Radiol*. 2016;45(4):437–446.
25. Rauch A, Arab WA, Dap F, Dautel G, Blum A, Gondim Teixeira PA. Four-dimensional CT analysis of wrist kinematics during radioulnar deviation. *Radiology*. 2018;289:750–758.
26. Kelly PM, Hopkins JG, Furey AJ, Squire DS. Dynamic CT scan of the normal scapholunate joint in a clenched fist and radial and ulnar deviation. *Hand (N Y)*. 2008;13:666–670.

27. Maizlin ZV, Vos PM. How to measure scapholunate and Cobb's angle on MRI and CT. *J Digit Imaging*. 2012;25(4):558–561.
28. Rajan PV, Day CS. Scapholunate ligament insufficiency. *J Hand Surg Am*. 2015;40(3):583–585.
29. Watson HK, Ballet FL. The SLAC wrist: scapholunate advanced collapse pattern of degenerative arthritis. *J Hand Surg Am*. 1984;9(3):358–365.
30. Megerle K, Pöhlmann S, Kloetetrs O, Germann G, Sauerbier M. The significance of conventional radiographic parameters in the diagnosis of schapholunate ligament lesions. *Eur Radiol*. 2011;21(1):176–181.
31. Cooney WP, Dobyns JH, Linscheid RL. Arthroscopy of the wrist: anatomy and classification of carpal instability. *Arthroscopy*. 1990;6(2):133–140.
32. Geissler WB, Freeland AE, Savoie FH, McIntyre LW, Whipple TL. Intracarpal soft-tissue lesions associated with an intra-articular fracture of the distal end of the radius. *J Bone Joint Surg Am*. 1996;78(3):357–365.
33. Messina JC, Van Overstraeten L, Luchetti R, Fairplay T, Mathoulin CL. The EWAS classification of scapholunate tears: an anatomical arthroscopic study. *J Wrist Surg*. 2013;2(2):105–109.
34. Zhao K, Breighner R, Holmes D III, Leng S, McCollough C, An KN. A technique for quantifying wrist motion using four-dimensional computed tomography: approach and validation. *J Biomech Eng*. 2015;137(7):0745011–0745015.
35. Geissler WB. Arthroscopic management of scapholunate instability. *J Wrist Surg*. 2013;2(2):129–135.