Skeletal Radiol (2016) 45:437–446
DOI 10.1007/s00256-015-2308-0

SCIENTIFIC ARTICLE

Scapholunate kinematics of asymptomatic wrists in comparison with symptomatic contralateral wrists using four-dimensional CT examinations: initial clinical experience

Shadpour Demehri[1] **· Nima Hafezi-Nejad**[1] **· John N. Morelli**[1] **· Uma Thakur**[1] **·**
Scott D. Lifchez[2] **· Kenneth R. Means**[3] **· John Eng**[1] **· Jaimie T. Shores**[2]

Received: 29 June 2015 / Revised: 4 November 2015 / Accepted: 30 November 2015 / Published online: 14 December 2015
© ISS 2015

Abstract
Objectives Using four-dimensional CT scan (4DCT), we aimed at showing the kinematics of scapholunate (SL) interval in asymptomatic wrists in comparison with symptomatic contralateral wrists with inconclusive radiographic findings.
Methods This is an IRB approved, HIPPA compliant, retrospective study. Patients suspected of SL interosseous ligament (SLIL) injuries were referred for further evaluation of chronic wrist pain (>3 months). Twelve wrists (11 subjects) with chronic symptoms and inconclusive plain radiographs and 10 asymptomatic wrists (in 10 different subjects) were scanned using 4DCT. The minimum SL interval was measured during three wrist motions: relaxed-to-clenched fist, flexion-to-extension, and radial-to-ulnar-deviation. Changes were recorded using double-oblique multiplanar reformation technique.
Results We extracted the normal limits of the SL interval as measured by dynamic CT scanning during active motion in asymptomatic wrists. In asymptomatic wrists, the average SL interval was observed to be smaller than 1 mm during all motions. In symptomatic wrists, during exams performed with clenched fist (SL interval (mean±SD)=2.53±1.19 mm), extension (2.54±1.48 mm) or ulnar deviation (2.06±1.12 mm), the average SL interval was more than 2 mm. In contrast to symptomatic wrists, no significant change in SL interval measurements was detected during wrist motions in asymptomatic wrists. There was a mild to moderate correlation between SL interval change and presence/absence of symptoms (point-biserial correlation coefficients: 0.29–0.55).
Conclusion In patients with wrist pain suspicious for SLIL injury and inconclusive radiographs, SL interval increase can be detected with 4DCT in the symptomatic wrist compared to the asymptomatic wrist.

Keywords Four-dimensional computed tomography · Scapholunate interosseous ligament injury · Kinematics · Chronic wrist pain

✉ Shadpour Demehri
demehri2001@yahoo.com

[1] Musculoskeletal Radiology, Russell H. Morgan Department of Radiology and Radiological Science, Johns Hopkins University, 601 N. Caroline Street, JHOC 5165, Baltimore, MD 21287, USA

[2] Department of Plastic and Reconstructive Surgery, Johns Hopkins University, Baltimore, MD, USA

[3] The Curtis National Hand Center, MedStar Union Memorial Hospital, Baltimore, MD, USA

Introduction

The scapholunate interosseous ligament (SLIL) injury is the most common cause of carpal instability [1, 2] and is associated with pain, tenderness, and mechanical symptoms [2, 3]. An untreated SLIL injury can compromise wrist function, cause persistent pain, and ultimately can lead to carpal instability and advanced secondary osteoarthritis (OA) [4]. Carpal instability is defined as a symptomatic wrist associated with abnormal kinematics during motion [2, 5]. Demonstrating the abnormal kinematic pattern has traditionally been performed by cineradiography examination [2]; however, the complex configuration of multiple carpal bones and their three-dimensional (3D) motion may not be optimally assessed using two-dimensional (2D) images obtained by cineradiography, which may be operator dependent [6].

Anatomic alterations are frequently evaluated by measuring the SL interval using plain radiographs when a diagnosis of SLIL injury is suspected [7]; however, increased SL interval can also be observed in normal subjects with no apparent symptoms [2, 6]. Radiography has been associated with sensitivity and specificity of 69 and 84 % in the detection of scapholunate dissociation [8]; thus, given the low accuracy of plain radiographs in the diagnosis of SLIL injury, new modalities are being utilized to address the issue more comprehensively [6, 9, 10]. Diagnostic performance of 3 T MRI imaging is superior to 1.5 T MRI in detection of SLIL injury, and has been associated with sensitivity of 65–89 % and specificity of close to 100 % [11, 12]. In other words, despite high specificity, MRI is insensitive for the diagnosis of subtle SLIL injuries, and therefore MR arthrography is often performed to improve the diagnostic accuracy (sensitivity of 72–85 and 100 % specificity [11, 12]), which is an invasive procedure and is still associated with high false negative rates [8–10, 13]. Moreover, neither of the aforementioned examinations may provide a dynamic evaluation of the symptomatic wrist and may not detect the subtle instabilities that are only apparent in active motion. In many patients with chronic wrist symptoms, noninvasive imaging fails to detect interosseous ligament injuries. Clinicians sometimes diagnose pre-dynamic SL instability, which is defined when conventional diagnostic modalities, including cineradiography, are inconclusive, but the physical examination is suggestive [6, 14]. Currently, arthroscopy is the most accurate method for the diagnosis of SLIL injury and is considered as "reference standard" [15]. Nevertheless, arthroscopy is an invasive procedure and is associated with several disadvantages including high cost, need for anesthesia and, postoperative morbidity, infection and neurovascular complications [16–18].

In contrast to cineradiography, four-dimensional CT scans (4DCT) using 320–row multi-detectors and 16-cm craniocaudal coverage provides high-resolution volumetric imaging of the wrist during motion. With a high temporal resolution, 4DCT scans have emerged as feasible, non-invasive, alternative imaging modalities in clinical settings in cases with inconclusive findings on plain radiography and MRI examinations that require diagnostic work-up using invasive procedures such as wrist arthroscopy [19, 20]. Owing to the ability to scan active wrist motions, 4DCT scans can detect dynamic changes in the small structures of the wrist with high-resolution 3D imaging [19–21]. Before performing a larger, prospective study to determine the "diagnostic accuracy" of 4DCT in detection of SLIL injury compared with the diagnostic arthroscopy as the "reference standard", in this project, we aimed to demonstrate the presence of abnormal kinematics (defined as changes in SL intervals during active wrist motions [2]) in chronically symptomatic wrists with inconclusive radiographs, but high clinical suspicion for SL instability. We further investigated the correlation between SL interval changes during active wrist motions and the presence/absence of symptoms, by using 4DCT data obtained from different patients' asymptomatic contralateral wrists. We hypothesized that in patients with chronic wrist symptoms and inconclusive plain radiographs, there may be dynamic changes in the SL interval during active wrist motion that is not detected in asymptomatic wrists.

Methods

This study was an Institutional Review Board (IRB) approved and Health Insurance Portability and Accountability Act (HIPAA) compliant retrospective study. We have performed 4DCT examinations in 27 patients with chronic wrist symptoms from December 2011 to May 2015. In all of these examinations, 4DCT scan was also acquired from the asymptomatic contralateral wrists (in a subgroup of patients with unilateral wrist pain). Nineteen symptomatic wrists underwent examination and were evaluated for SL instability. All referred patients had physical examination findings suggestive of SL instability including tenderness over the dorsal scapholunate interval (distal to Lister's tubercle) and/or positive Watson test results (corresponding to pain, tenderness or clunk in the scaphoid shift test) [15]. All patients were referred by two board-certified hand surgeons for suspected diagnosis of SLIL injury. Among these 19 symptomatic wrists, five wrists demonstrated SL interval measurements of 3 mm or more in the plain radiograph, which was suggestive of SL instability [2, 22], and were excluded from the study, while two more wrists were excluded as they had an accompanying Madelung deformity. Finally, 12 wrists (in 11 patients) with chronic wrist pain either following prior distal radius fracture or scaphoid fracture (6 wrists with fractures, 4 of which were status post-surgical fixation with metallic hardware) or with no history of acute trauma (6 wrists) were included. Each of the 12 symptomatic wrists had radiographs with "inconclusive" findings, defined as SL intervals of less than 3 mm (12 wrists with normal imaging in the presence of abnormal physical examination) [2, 22]. Additionally, none of the symptomatic wrists had evidence of scapholunate advanced collapse; of these patients, seven had simultaneous MRI, and one underwent arthroscopy following the 4DCT examination. The MRI examinations were evaluated by a musculoskeletal radiologist with 5 years of experience, and SLIL injuries were graded according to a previously described grading system (grade 1: peri ligamentous edema; grade 2: partial tears or weakening with thickening due to peri and intra-ligamentous edema; grade 3: complete disruption) [23]. To compare measurements between the symptomatic and asymptomatic wrists, in 10 different patients with unilateral wrist symptoms, the 4DCT data of the asymptomatic contralateral wrists were analyzed. The surgeons also did not identify any abnormality during clinical examination of the asymptomatic wrists.

The 4DCTs were performed using a 320-row-detector CT scanner (Aquilion ONE; Toshiba, Tokyo, Japan) with a tube potential of 100 kV, a 100-mA-second current and using adaptive iterative dose reduction (AIDR) construction algorithm, which was followed by SL interval measurements using Vitrea post-processing software (Vital Images, a Toshiba Medical Systems Company, Minnetonka, MN). Using a double oblique multi-planar reconstruction (MPR) technique, we defined our "primary" and "secondary" planes [21]. This MPR technique had been previously shown to be feasible and reliable for the evaluation of small wrist bones and their interval measures [21, 24, 25]. The "primary" axial plane was defined as the plane perpendicular to the radius and ulnar distal meta-diaphysis (Fig. 1). The "primary" sagittal plane was defined by anterior and posterior margins of the ulnar's sigmoid notch (Fig. 2). The "primary" coronal plane was defined using the ulnar's and radial's styloid processes (Fig. 3). Finally, we determined an "oblique" sagittal plane, which was adjusted so that the SL interval would present in the centerline (Fig. 4). Using the "oblique" sagittal plane, we determined the "oblique" axial plane through the SL interval. Since the SL interval was not uniform along the oblique sagittal plane, the minimum SL interval measurement was determined and used for this study (Fig. 5). With the oblique sagittal plane placed in the middle of the 3D space between scaphoid and lunate, the oblique axial plane could show a 2D view of the scaphoid, lunate, and their interval. Scrolling on this oblique axial plane brought the third dimension into the observers' vision; allowing the observer to surf along the SL interosseous space while viewing the SL interval in consecutive planes. In 4DCT scans, SL interval changes were evaluated during three standard wrist motions, each performed within 5 s: (1) relaxed grip to clenched fist; (2) flexion to extension; (3) radial deviation to ulnar deviation. During each motion, 11 consecutive volumes of CT scan acquisitions were performed to track the corresponding carpal bone motions (0–5 s; temporal resolution: 0.5 s). Total scanning time for the three motions was 15 s per wrist. Since SL interval measurements could be affected by plane, section thickness, and display window setting, we predefined the "oblique axial" plane, and used the thin section (0.6 mm) using the MPR technique in bone window setting to measure SL interval. We preformed all the measurements using the aforementioned setting to minimize variability in measurement setting. All measurements were performed by two musculoskeletal radiologists with 5 and 1 years of experience, respectively. Measures of radiation exposure including CT dose and dose length product were recorded for each examination. A lead shield was used for protection of each patients' torso, gonads, and thyroid. Positions and views of the plain radiographs (which were used to select the eligible wrists) were in line with previous studies [6, 8]. Plain radiographs were obtained in at least three standard views including anteroposterior, lateral and oblique.

Age, gender and a previous history of acute trauma were obtained from patients' electronic chart. Wrist MRI images were interpreted by a fellowship-trained musculoskeletal radiologist (with 5 years of experience). In three cases, MRI was not performed due to the presence of metallic hardware.

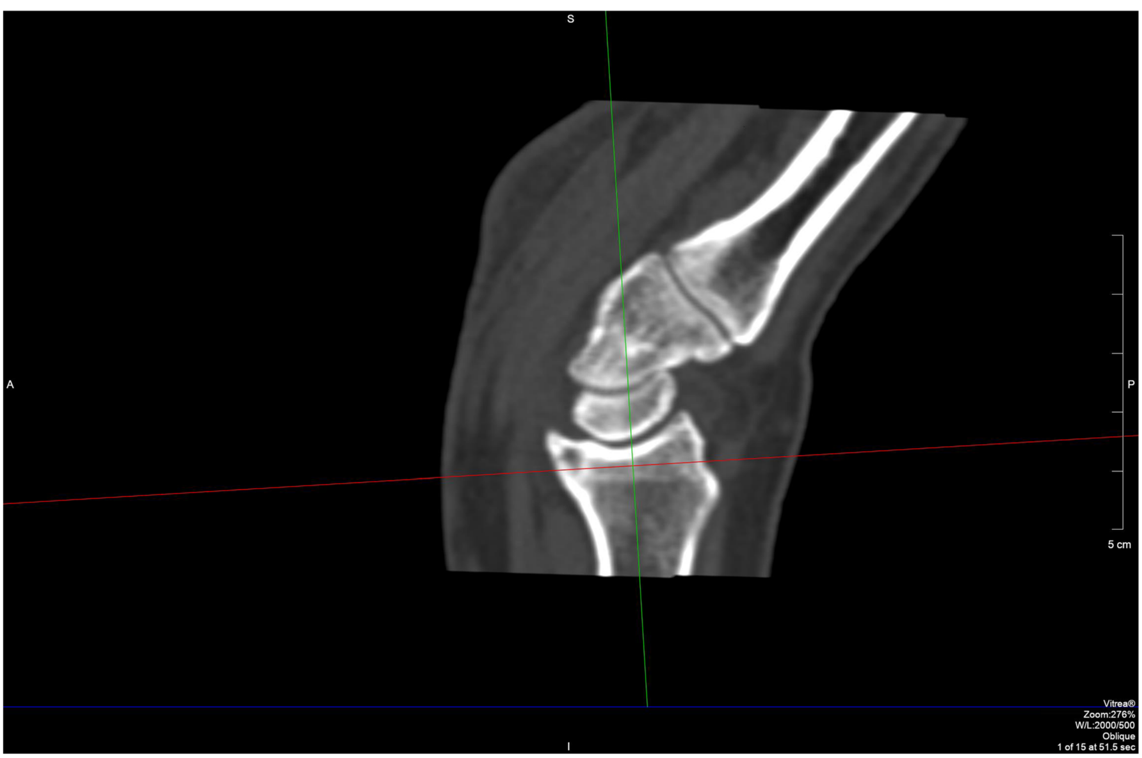

Fig. 1 The primary axial plane; defined as the plane perpendicular to the radius and ulnar distal meta-diaphysis

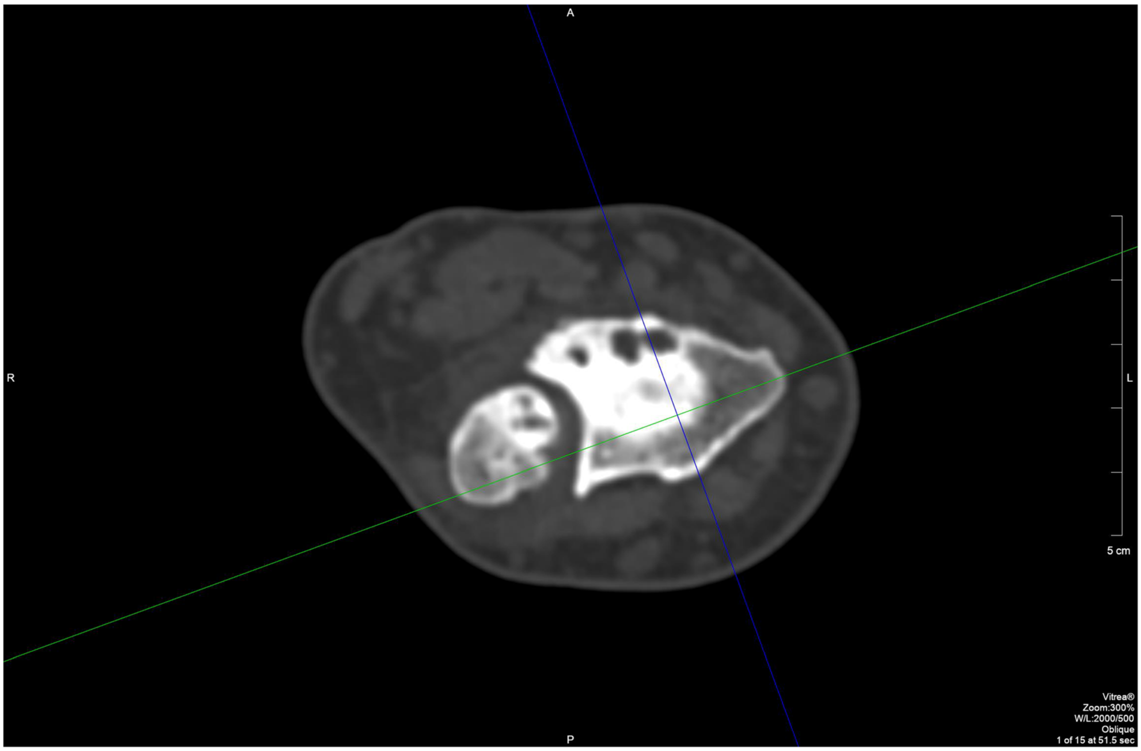

Fig. 2 The primary sagittal plane; defined by anterior and posterior margins of the ulnar's sigmoid notch

Medical records were also searched for the availability of arthroscopy reports.

Distributions of the obtained SL intervals were assessed using a non-parametric Kolmogorov-Smirnov test (none violated the assumption of normality). A paired t-test was used to compare the SL interval measurement changes during each set of active wrist motions. To investigate the robustness of our results, we aimed at evaluating the difference in the SL

Fig. 3 The primary coronal plain; defined using the ulnar and radial styloid processes

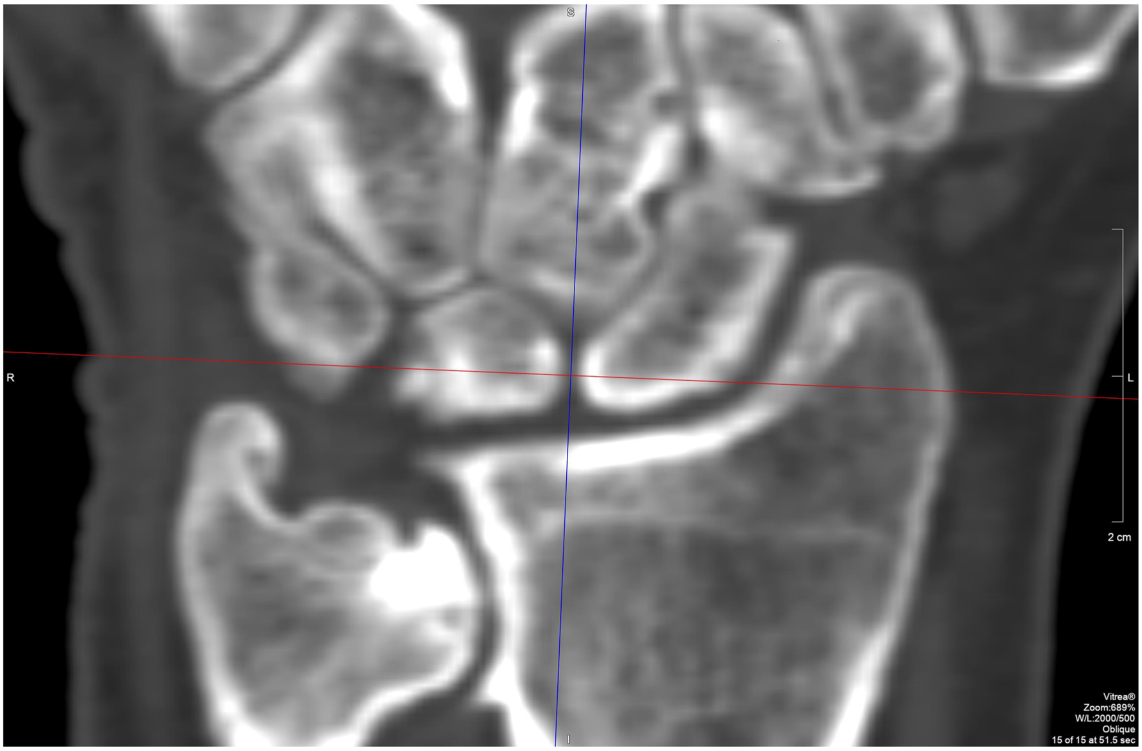

Fig. 4 An oblique sagittal plane; adjusted so that the SL interval presents in the centerline

interval measurements and their correlation with the presence of wrist symptoms in a subgroup analysis by including cases with confirmed SLIL injury (using MRI or diagnostic arthroscopy). As mentioned earlier, diagnostic arthroscopy is considered as the reference standard for the evaluation of a suspected SLIL injury. Meanwhile, studies have shown that MRI examination can also be a specific (but not necessarily sensitive) tool in the detection of SLIL injuries [12]. We extracted the symptomatic cases who had a confirmed SLIL injury (either using MRI or arthroscopy) and re-analyzed the data. Our purpose was to confirm a similar trend of results among subjects with confirmed SLIL injury. Finally, correlation of the SL interval changes during each of the three motions with the presence/absence of symptoms was assessed using point-biserial correlation coefficients. A P-value<= 0.05 was set as the threshold of significance and analyses were performed using SPSS (v.18, Chicago, IL).

Results

Data from 12 symptomatic wrists with inconclusive radiographic findings and ten asymptomatic wrists (in different patients) who underwent 4DCT scan, were analyzed. There was no significant difference between age and gender of the symptomatic and asymptomatic subjects. Symptomatic and asymptomatic subjects (n=12 and 10, respectively) had an average age of 49±16 and 42±13 years, respectively (P value: 0.26). Similarly, symptomatic and asymptomatic subjects had 50 and 60 % females, respectively (P value for comparison: 0.66). Table 1 demonstrates the radiation exposure data for 4DCT examinations. The effective radiation dose (ERD) was calculated by multiplying the dose length product by a conversion factor of 0.0001, which is used for distal extremities [26]. Table 1 demonstrates the clinical descriptions of the included subjects with symptomatic wrists. Five subjects (one bilateral: six wrists) had chronic wrist pain with no recorded history of acute trauma. Six subjects had a prior history of fractures of the distal radius, ulna or scaphoid bones. Of these six subjects, four had metallic hardware adjacent to their symptomatic wrist. Two subjects with scaphoid fracture had a metallic hardware (screw placement) in their scaphoid bones. MRI was performed on seven patients, and in one patient MRI was performed after hardware removal. One patient had a history of arthroscopy.

Table 2 reports the SL interval measurements after each active motion with 95 % confidence intervals. Except for the endpoint in the clenched fist motion (SL interval: 0.51–1.34 mm), the SL interval was observed to remain<1 mm among the asymptomatic wrists. However, no symptomatic wrist was observed to have an average SL interval of less than 2 mm (Table 2) in clenched fist, ulnar deviation, and flexion positions during 4DCT examinations. In performing the three standard wrist motions, the changes in the SL interval measurements were significant in symptomatic, but not the asymptomatic wrists (Table 3). The average SL interval

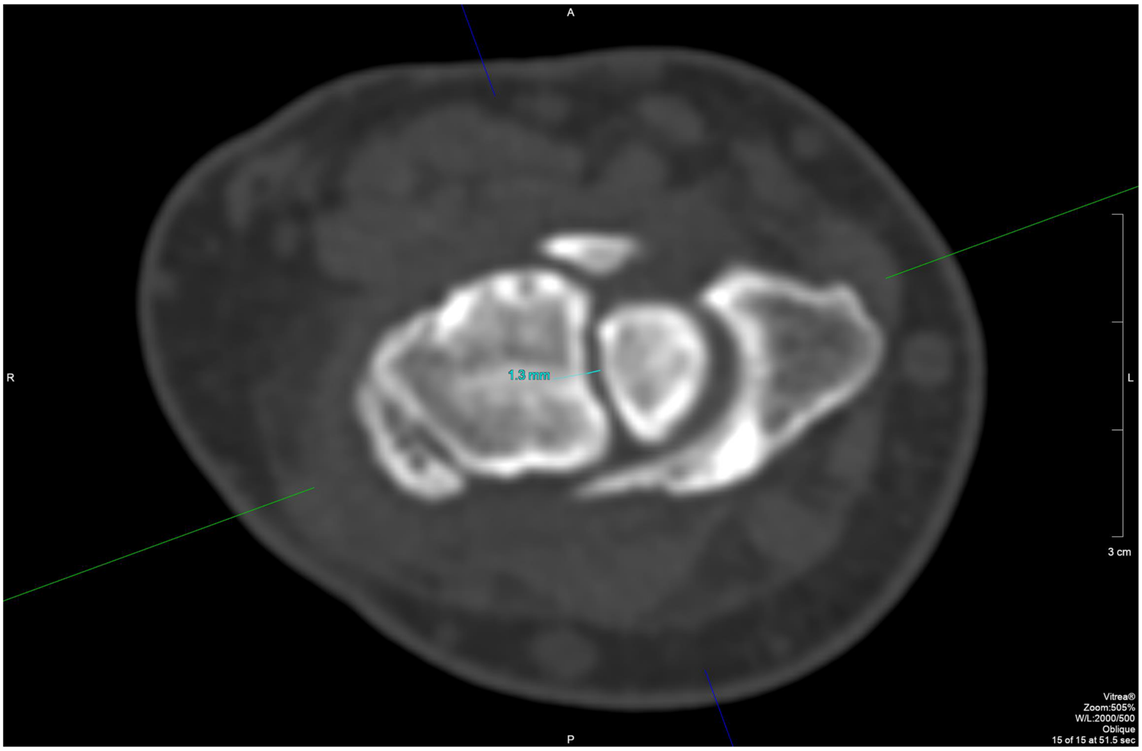

Fig. 5 The oblique axial plane through the SL interval; the minimum measurement was determined

measurement change from relaxed to the clenched position was 0.70±0.68 and 0.19±0.45 mm in the symptomatic and asymptomatic wrists, respectively. During wrist motion from flexion to extension, symptomatic wrists had 1.04±1.15 mm increases in the SL interval, while no average change was seen among the asymptomatic wrists (0.00±0.28 mm). During

Table 1 Clinical characteristics and radiation exposure details of the study patients presenting with chronic wrist pain

Age	Gender	History of acute trauma	Metallic hardware	MRI findings	Arthroscopy
47	F	No	No	SL ligament tear: grade I Volar band	N/A
75	M	No	No	N/A	N/A
38	M	Fall: scaphoid Fx	No	SL ligament tear: grade II volar	N/A
21	F	MVA: scaphoid Fx	Yes	SL ligament Tear: grade II dorsal	N/A
70	F	Fall: Barton Fx	No	SL ligament tear: grade II dorsal	N/A
59	F	No	No	SL ligament tear: grade I dorsal	N/A
51	F	Distal radio ulnar Fx	Yes	N/A	N/A
64	M	Fall: distal radius Fx	Yes	N/A	N/A
26	M	Fall: scaphoid Fx	Yes	N/A	N/A
47	M	No	No	Right: SL ligament tear: grade II dorsal Left: SL ligament tear: grade II volar	N/A
47	F	Fall	No	N/A	Yes
Studied wrist		Asymptomatic wrists		Symptomatic wrists	
CTD (mGy)		46.28±12.02		74.50±78.13	
Dose length product (mGycm)		445.30±122.04		606.46±619.86	
Effective radiation (mSv)		0.05±0.01		0.06±0.06	

N/A not available; *Fx* fracture; *MVA* motor vehicle accident; Ligament injuries: grade 1: peri ligamentous edema; grade 2: partial tears or weakening with thickening due to peri and intra ligamentous edema; grade 3: complete disruption. Values are mean±standard deviation (SD)

Table 2 Scapholunate interval measurements during active wrist motions

	SL interval mm (mean±SD)	95 % CI
Group A:	Asymptomatic wrists with normal plain radiography (n=10)	
Relaxed	0.73±0.23	0.55–0.91
Clenched	0.92±0.54	0.51–1.34
Flexion	0.76±0.33	0.52–1.00
Extension	0.76±0.35	0.51–1.01
Radial deviation	0.67±0.16	0.54–0.79
Ulnar deviation	0.68±0.30	0.45–0.91
Group B:	Symptomatic wrists with inconclusive plain radiography (n=12)	
Relaxed	1.83±0.84	1.26–2.39
Clenched	2.53±1.19	1.73–3.33
Flexion	1.50±0.49	1.17–1.83
Extension	2.54±1.48	1.54–3.53
Radial deviation	1.57±0.65	1.16–1.99
Ulnar deviation	2.06±1.12	1.35–2.77
Group C:[a]	Symptomatic wrists with inconclusive plain radiography and confirmatory MRI or arthroscopy (n=8)	
Relaxed	1.64±0.81	0.90–2.39
Clenched	2.47±1.27	1.29–3.65
Flexion	1.67±0.46	1.24–2.10
Extension	2.50±1.54	1.08–3.92
Radial deviation	1.60±0.73	0.99–2.21
Ulnar deviation	1.80±0.81	1.13–2.47

[a] Group C is a subgroup from group B

wrist motion from radial deviation to the ulnar deviation, an average 0.48±0.81 mm SL interval increase was seen among the symptomatic wrists. The observed motion of the asymptomatic wrists was minimal (0.01±0.35). In a subgroup analysis, a similar trend of SL interval change was observed among the eight wrists with abnormal findings suggestive of SLIL injuries as evidence by either MRI or arthroscopy (Table 3).

A mild to moderate positive correlation was observed (point-biserial correlation coefficients: 0.29–0.55) between the presence of symptoms and dynamic changes in the SL interval during all motions. Table 4 demonstrates the correlation coefficients for the three standard motions.

Discussion

Four-dimensional CT examination is a novel imaging technique that provides peripheral joint imaging during unconstrained active motions [19]. Despite extensive previous work in describing the kinematic patterns of carpal bones, a high-resolution 3D imaging may best detect abnormal relative carpal motion and position. This is now clinically feasible using 4DCT examination [19, 27] Akin to coronary CT angiogram, using 4DCT and double-oblique multiplanar reformation (MPR) technique, we can now quantify carpal bone motion abnormalities using predefined planes [19, 25]. In this study, we demonstrated the abnormal SL interval changes observed during active wrist motion in patients with clinical suspicion of SLIL injury and inconclusive radiographs. By mimicking the very same carpal motion in asymptomatic wrists, we showed the capability of 4DCT imaging in detecting SL instability when radiographs are non-diagnostic in patients with chronic wrist pain [9, 22, 28, 29]. These results suggest that perhaps the definition of an "inconclusive" radiograph based on a 3 mm cut-off is not adequately sensitive and advanced evaluations should be performed in persistently symptomatic

Table 3 Paired comparisons of the scapholunate interval changes during active wrist motions

	SL interval change mm (mean±SD)	SL interval change mm (95 % CI)	Paired t-test (P value)
Group A:	Asymptomatic wrists with normal plain radiography (10 wrists)		
Relaxed to clenched	0.19±0.45	–0.16–0.54	0.247
Flexion to extension	0.00±0.28	–0.20–0.20	1.00
Radial to ulnar deviation	0.01±0.35	–0.26–0.28	0.926
Group B:	Symptomatic and inconclusive plain radiography (12 wrists)		
–Relaxed to clenched	0.70±0.68	0.24–1.16	0.01
–Flexion to extension	1.04±1.15	0.26–1.81	0.01
–Radial to ulnar deviation	0.48±0.81	–0.03–1.00	0.06
Group C:[a]	Symptomatic and inconclusive plain radiography and confirmatory MRI or arthroscopy (8 wrists)		
–Relaxed to clenched	0.83±0.77	0.11–1.54	0.03
–Flexion to extension	0.83±1.18	–0.26–1.92	0.11
–Radial to ulnar deviation	0.20±0.32	–0.07–0.47	0.12

[a] Group C is a subgroup from group B

Table 4 Correlation of the scapholunate interval change with presence/absence of symptoms

	Relaxed to clenched	Flexion to extension	Radial to ulnar deviation
Excluding wrists with diagnostic plain radiography (SL interval>3 mm) (22; 10 asymptomatic and 12 symptomatic)	0.41 (0.07)	0.53 (0.01)	0.35 (0.12)
Excluding wrists without MRI/Arthroscopy confirmation (18; 10 asymptomatic and 8 symptomatic)	0.48 (0.06)	0.49 (0.05)	0.29 (0.26)

Correlations are presented as point-biserial correlation coefficients (*P* values)

wrists even with smaller SL intervals. Possibly it should have been 1 mm or less. Of the 12 symptomatic wrists, 6 had a previous history of acute trauma prior to their symptoms. The preceding trauma was either fracture of the distal radius or scaphoid. A high prevalence of SL injuries has been reported in patients with distal radius fracture. In our case series, it is not surprising that this was also observed (four cases, or 33 %) [29]. In patients with metallic hardware in place after surgical treatment distal radius fracture, MRI image quality for the detection of SLIL injury can be affected due to associated susceptibility artifact. Many of these patients may be evaluated using 2D cine fluoroscopy to evaluate for carpal instability.

In this study, we defined the reference limits of SL interval during active motion in asymptomatic wrists and compared them with corresponding measurements obtained from symptomatic wrists using 4DCT (Table 2). Based on our observations, the SL interval is expected to be smaller than 1 mm in asymptomatic wrists (except for the clenched fist; 95 % confidence interval (CI): 0.51–1.34 mm), and larger than 1 mm in symptomatic wrists. In fact, in clenched fists, during extension, or ulnar deviation, the average observed SL interval in symptomatic wrists was>2 mm (Table 2).

Previous studies that investigated common wrist motion abnormalities were limited to the use of cineradiography and fluoroscopy [6, 22, 30]; thus, they all had similar limitations including the unavailability of 3D imaging and the use of active motion. To the best of our knowledge, no previous study has ever compared the SL intervals in symptomatic and asymptomatic wrists using 4DCT scan acquisitions. The clinical potential of 4DCT scan acquisition is highlighted in other reports that utilized the MPR technique as a feasible methodology to be implemented in routine clinical practice [21, 25]. In this study, we successfully defined the increased SL interval changes during active motion in our symptomatic patients. In fact, patients with persistent wrist pain and inconclusive radiographs may benefit from 4DCT examination to demonstrate associated carpal instability [29] using active motion analysis [6]. Moreover, our study also shows the correlation between the degree of SL interval change in dynamic motion [2] with the presence of symptoms. While symptomatic wrists had significant changes in the SL interval during standard motions, there was no SL interval measurement change among the asymptomatic joints. A previous cadaver study associated variable bony anatomy of the radius and scaphoid with added wrist constraint in the setting of induced ligamentous injury [31], proposing that symptoms were related to the different levels of instability between wrists with favorable versus unfavorable geometric characteristics [31]. Our study adds an in-vivo evaluation to support the hypothesis that patients' symptoms do correlate with the degree of observed instability.

In this study, MRI was able to detect SLIL injury in seven patients. Meanwhile, all symptomatic wrists had significant SL interval changes during motion in 4DCT evaluations. Previous reports have highlighted the low diagnostic accuracy of MRI in detecting established SLIL injuries [9, 13] and, thus, there is a need for more sophisticated evaluations in inconclusive cases [9, 10]. We propose 4DCT scan as a possible alternative to detect motion abnormalities when SLIL injury is the suspected diagnosis [19], especially when MRI acquisition can be challenging due to the presence of metallic hardware as a result of a concomitant fracture.

Since increased radiation exposure is one of the main concerns in 4DCT examinations, we managed to record and present the CT radiation dose (mGy), dose length products (DLP – mGycm) and effective radiation dose (ERD – mSy) of the examinations in our study. Regarding dynamic CT acquisition, following our previous experience [24], we used a 100 mAs instead of the current standard of 200 mAs (as described by Leng et al. [19]). With this modification, our DLPs (445.30±122.04 for asymptomatic and 606.46±619.86 for symptomatic wrists) were much below 2,000 mGycm—the threshold to induce skin erythema. In terms of effective radiation, the ERDs for symptomatic and asymptomatic subjects in our study were 0.05±0.01 and 0.06±0.06, respectively. This is much less than an average chest CT scan with an estimated ERD of 5.27±1.68 mSy, and even smaller than an average chest plain radiograph with an estimated ERD of 0.08 mSy [26]. In fact, the small conversion factor (approximately 0.0001) for wrist and distal extremities, results in a much smaller ERDs, when compared to the body or proximal extremity scans [26].

Limitations and summary

This study has several limitations. First, we did not determine the diagnostic accuracy of 4DCT compared with wrist arthroscopy ("reference standard") as this was not performed in all symptomatic wrists to confirm and grade SLIL injury. However, the main goal of our study was to demonstrate the presence of SL instability using 4DCT acquisition with double oblique MPR and to demonstrate the significantly increased SL intervals in symptomatic joints. Second, we could only correlate the presence/absence of symptoms with SL interval changes. Quantitative measurement of patients' symptoms could have provided more information for correlation between the degree of SL instability and quantitative metrics for symptom characterization. Third, although the observer was not aware of the status of wrists during 4DCT measurements (symptomatic versus asymptomatic), in some cases (e.g. in symptomatic wrists with metallic hardware), the observer could not have been completely blinded during measurements. Fourth, this study did not evaluate the measurement or assessment of the scapholunate angle on wrist radiograph or 4DCT to further evaluate the abnormal kinematics of carpal bones during various wrist motions. It was not clinically feasible to obtain plain radiographs in all of the positions that were involved in the 4DCT examinations; however, such sophisticated views might have detected SLIL interval widening in some cases, which were labeled as "inconclusive" in plain radiograph. Meanwhile, cineradiography was not a part of this study either. Our extracted SL intervals for symptomatic and asymptomatic wrists (Table 2) may be used as a reference for cineradiographic assessments (obtained in the specified wrist positions). Nevertheless, unlike 4DCT, cineradiologic images cannot be analyzed using the reconstruction techniques that are available for CT examinations. Without MPR, surfing the 3D space between the scaphoid and lunate bones for the minimum interosseous interval can be challenging, operator dependent and prone to inaccuracy. Finally, the results of our study, though large in their effect size, are limited in the number of involved cases. Due to the limited number of patients fulfilling the specific inclusion criteria of our study (chronic wrist pain and instability with inconclusive radiography and less than 3 mm of SL interval), we could not manage to find one by one matches to prevent further loss of the sample size. However, we made sure that there was no significant (neither statistically nor clinically significant) difference between the age and gender of the symptomatic and asymptomatic subjects. Future evaluations of a larger group of symptomatic wrists may improve our understanding of SL instability concerning patient-reported symptoms.

In summary, in comparison with asymptomatic wrists, SL intervals increased during active motion in symptomatic wrists that had inconclusive plain radiographs (as seen on 4DCT examinations). Also, 95 % confidence intervals that are listed in this study may be used to establish normalcy value ranges during 4DCT examinations.

Compliance with ethical standards

Conflicts of interest Shadpour Demehri has grants from GERRAF 2014–2016; Carestream Health Inc. 2013–2015 for Cone – Beam CT clinical trial; Toshiba Medical Systems as a consultant. Other authors declare no conflicts of interest. This study is an IRB approved, HIPAA compliant study (approved by the institutional review board of the Johns Hopkins University).

References

1. Willebrand J. Scapholunate instability: diagnosis–classification–treatment. Orthopade. 1999;28(10):878–82.
2. Kitay A, Wolfe SW. Scapholunate instability: current concepts in diagnosis and management. J Hand Surg. 2012;37(10):2175–96.
3. Pappou IP, Basel J, Deal DN. Scapholunate ligament injuries: a review of current concepts. Hand. 2013;8(2):146–56.
4. O'Meeghan CJ, Stuart W, Mamo V, Stanley JK, Trail IA. The natural history of an untreated isolated scapholunate interosseous ligament injury. J Hand Surg (Br). 2003;28(4):307–10.
5. Moritomo H, Apergis EP, Garcia-Elias M, Werner FW, Wolfe SW. International Federation of Societies for Surgery of the Hand 2013 Committee's report on wrist dart-throwing motion. J Hand Surg. 2014;39(7):1433–9.
6. Pliefke J, Stengel D, Rademacher G, Mutze S, Ekkernkamp A, Eisenschenk A. Diagnostic accuracy of plain radiographs and cineradiography in diagnosing traumatic scapholunate dissociation. Skelet Radiol. 2008;37(2):139–45.
7. Manuel J, Moran SL. The diagnosis and treatment of scapholunate instability. Hand Clin. 2010;26(1):129–44.
8. Gradl G, Neuhaus V, Fuchsberger T, Guitton TG, Prommersberger KJ, Ring D, et al. Radiographic diagnosis of scapholunate dissociation among intra-articular fractures of the distal radius: interobserver reliability. J Hand Surg. 2013;38(9):1685–90.
9. Schadel-Hopfner M, Iwinska-Zelder J, Bohringer G, Braus T, Klose KJ, Gotzen L. MRI or arthroscopy in the diagnosis of scapholunate ligament tears in fractures of the distal radius? Handchir Mikrochir Plast Chir. 2001;33(4):234–8.
10. Prosser R, Harvey L, Lastayo P, Hargreaves I, Scougall P, Herbert RD. Provocative wrist tests and MRI are of limited diagnostic value for suspected wrist ligament injuries: a cross-sectional study. J Geophys Res. 2011;57(4):247–53.
11. Lee YH, Choi YR, Kim S, Song HT, Suh JS. Intrinsic ligament and triangular fibrocartilage complex (TFCC) tears of the wrist: comparison of isovolumetric 3D-THRIVE sequence MR arthrography and conventional MR image at 3 T. Magn Reson Imaging. 2013;31(2):221–6.
12. Magee T. Comparison of 3-T MRI and arthroscopy of intrinsic wrist ligament and TFCC tears. AJR Am J Roentgenol. 2009;192(1):80–5.
13. Schadel-Hopfner M, Iwinska-Zelder J, Braus T, Bohringer G, Klose KJ, Gotzen L. MRI versus arthroscopy in the diagnosis of scapholunate ligament injury. J Hand Surg (Br). 2001;26(1):17–21.
14. Dyer GS. Predynamic scapholunate instability. J Hand Surg. 2010;35(11):1879–80.
15. Chim H, Moran SL. Wrist essentials: the diagnosis and management of scapholunate ligament injuries. Plast Reconstr Surg. 2014;134(2):312e–22.
16. El-Gazzar Y, Baker 3rd CL, Baker Jr CL. Complications of elbow and wrist arthroscopy. Sports Med Arthrosc. 2013;21(2):80–8.
17. Fernandes CH, Miranda CD, Dos Santos JB, Faloppa F. A systematic review of complications and recurrence rate of arthroscopic resection of volar wrist ganglion. Hand Surg. 2014;19(3):475–80.
18. Slutsky DJ, Trevare J. Scapholunate and lunotriquetral injuries: arthroscopic and open management. Sports Med Arthrosc. 2014;22(1):12–21.
19. 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.
20. Garcia-Elias M, Alomar Serrallach X, Monill SJ. Dart-throwing motion in patients with scapholunate instability: a dynamic four-dimensional computed tomography study. J Hand Surg Eur. 2014;39(4):346–52.
21. Demehri S, Wadhwa V, Thawait GK, Fattahi N, Means KR, Carrino JA, et al. Dynamic evaluation of pisotriquetral instability using 4-dimensional computed tomography. J Comput Assist Tomogr. 2014;38(4):507–12.

22. Kwon BC, Baek GH. Fluoroscopic diagnosis of scapholunate interosseous ligament injuries in distal radius fractures. Clin Orthop Relat Res. 2008;466(4):969–76.
23. Chhabra A, Soldatos T, Thawait GK, Del Grande F, Thakkar RS, Means Jr KR, et al. Current perspectives on the advantages of 3-T MR imaging of the wrist. Radiogr Rev Publ Radiol Soc North Am Inc. 2012;32(3):879–96.
24. Demehri S, Hafezi-Nejad N, Thakur U, Morelli JN, Lifchez SD, Means KR, et al. Evaluation of pisotriquetral motion pattern using four-dimensional CT: initial clinical experience in asymptomatic wrists. Clin Radiol. 2015 Dec;70(12):1362–9.
25. 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.
26. Biswas D, Bible JE, Bohan M, Simpson AK, Whang PG, Grauer JN. Radiation exposure from musculoskeletal computerized tomographic scans. J Bone Joint Surg Am. 2009;91(8):1882–9.
27. Goh YP, Lau KK. Using the 320-multidetector computed tomography scanner for four-dimensional functional assessment of the elbow joint. Am J Orthop (Belle Mead NJ). 2012;41(2):E20–4.
28. Pilny J, Kubes J, Hoza P, Mechl M, Visna P. Scapholunate instability of the wrist following distal radius fracture. Acta Chir Orthop Traumatol Cech. 2007;74(1):55–8.
29. Welling RD, Jacobson JA, Jamadar DA, Chong S, Caoili EM, Jebson PJ. MDCT and radiography of wrist fractures: radiographic sensitivity and fracture patterns. AJR Am J Roentgenol. 2008;190(1):10–6.
30. Hohendorff B, Burkhart KJ, Stein G, Muhldorfer-Fodor M, Muller LP. Traction radiography for the diagnosis of scapholunate ligament tears: an experimental cadaver study. J Hand Surg Eur. 2012;37(5):453–8.
31. Werner FW, Short WH, Green JK, Evans PJ, Walker JA. Severity of scapholunate instability is related to joint anatomy and congruency. J Hand Surg. 2007;32(1):55–60.