A BROAD SCOPE OF WRIST INSTABILITY

Osseous & Ligamentous Pathology

Prediction, evaluation, and treatment optimization

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LIST OF ABBREVIATIONS

AI	Artificial intelligence
AP	Anterior-posterior
CT	Computed tomography
DIC	Dorsal intercarpal ligament
DRC	Dorsal radiocarpal ligament
DRF	Distal radius fracture
DRUJ	Distal radioulnar joint
DUC	Dorsal ulnar corner
LRL	Long radio lunate ligament
MRI	Magnetic resonance imaging
ROM	Range of motion
RSC	Radioscaphocapitate ligament
SL	Scapholunate
SLIL	Scapholunate interosseous ligament
SRL	Short radio lunate ligament
STT	Scaphotrapeziotrapezoid
TFCC	Triangular fibrocartilage complex
PA	Posterior-anterior
ORIF	Open reduction and internal fixation

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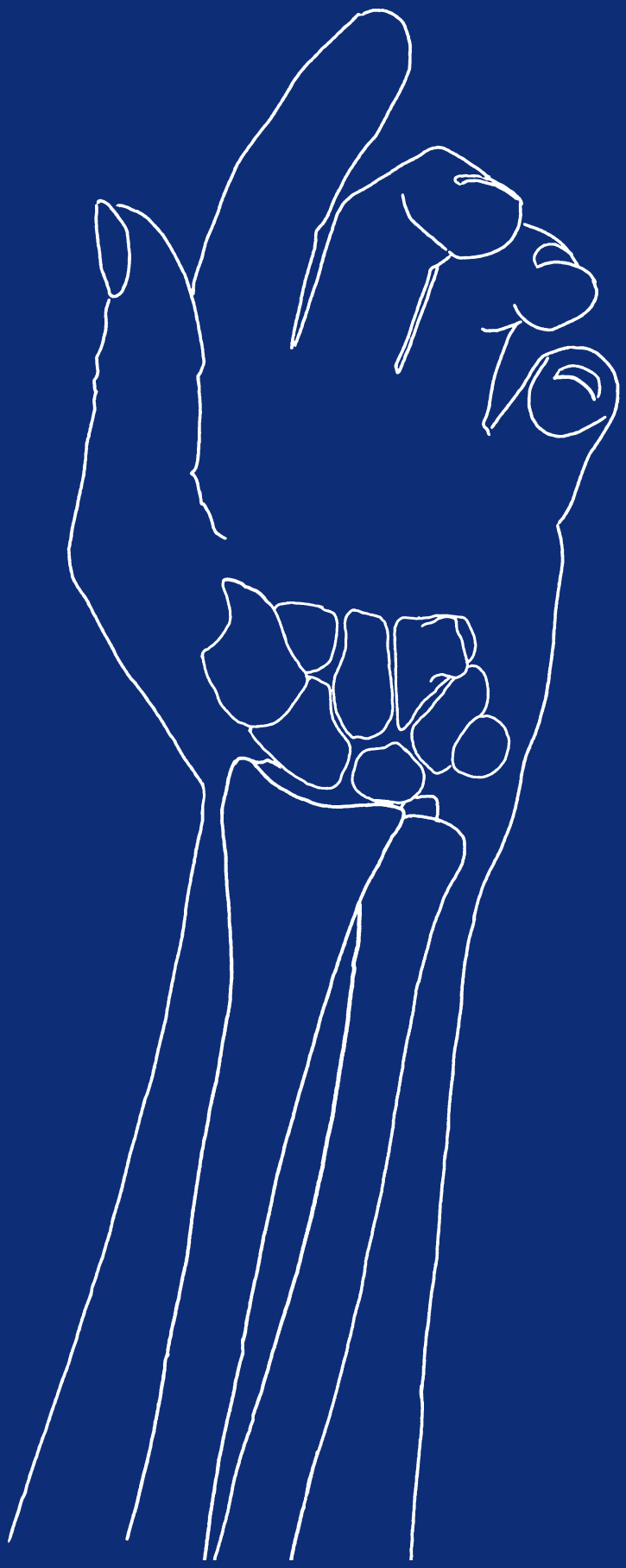

CHAPTER 1

General introduction, aim, and outline of this thesis

GENERAL INTRODUCTION

Anatomy and stability of the wrist

The wrist joint is a complex structure that plays a crucial role in the mobility and stability of the distal upper extremity. It comprises multiple osseous components, including the distal radius, the ulna, and the carpal bones (Figure 1), interconnected by an intricate network of ligaments. Together, these osseous and ligamentous structures support the functional integrity of the wrist, forming and stabilizing key joints, such as the radiocarpal joint, distal radioulnar joint (DRUJ), ulnocarpal joint, and intercarpal joints. These joints must balance mobility and the capacity to withstand significant mechanical forces, often referred to as stability. Injury to any of these structures, whether the osseous or ligamentous components in the wrist, may lead to instability of this complex joint.

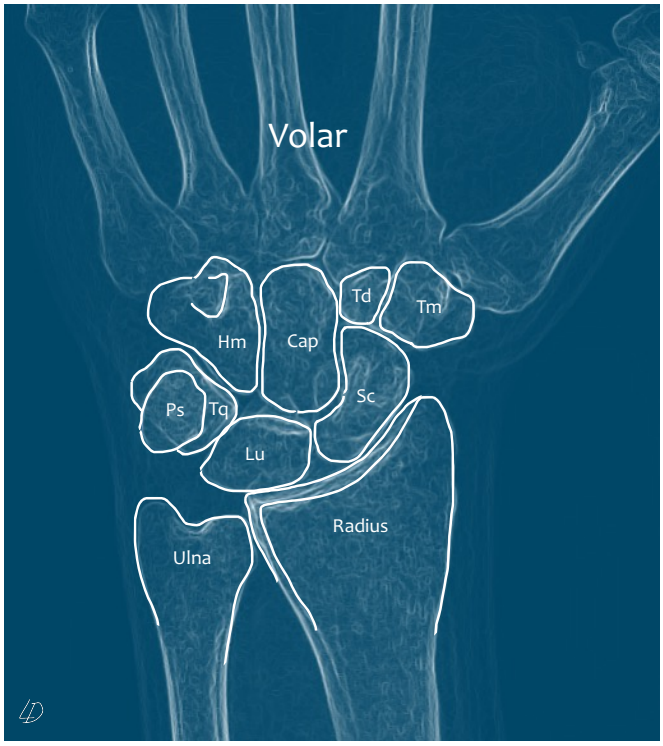

Figure 1. Anatomy of the wrist; Hm: hamate; Cap: capitate; Td: trapezoid; Tm: trapezium; Tq: triquetrum; Ps: Pisiform; Lu: lunate; Sc: scaphoid;

Osseous instability - Distal radius fractures

Among the most common injuries in the upper extremity is the distal radius fracture (DRF), with an increasing incidence in older patients (>65 years) (1-3). The radial bone comprises the largest artificial surface of the wrist joint. Fractures to the distal part of the radius often disrupt radiocarpal stability and could cause malalignment and pain. This can lead to significant functional impairment, affecting hand and wrist mobility in both the short and long term. Eventually, compromising range of motion (ROM) substantially impacting the quality of life, such as impaired daily activities and work, reducing overall physical independence (2). Therefore, it is essential to diagnose and

treat these, sometimes complex fractures accurately to maintain the wrist's normal physiology (5).

Diagnosis of distal radius fractures

Diagnosing distal radius fractures is subject of debate. Fracture alignment is traditionally assessed by posterior-anterior (PA) and lateral radiographs (5). In the Dutch guidelines, correct fracture alignment is defined as < 10° dorsal angulation, < 20° volar angulation, < 2-millimeter step-off intra-articular, < 3-millimeter radial shortening, > 15° radiale inclination, absent translation and intact radiocarpal alignment in the lateral image and absent significant translation in the PA image (5) (Figure 2).

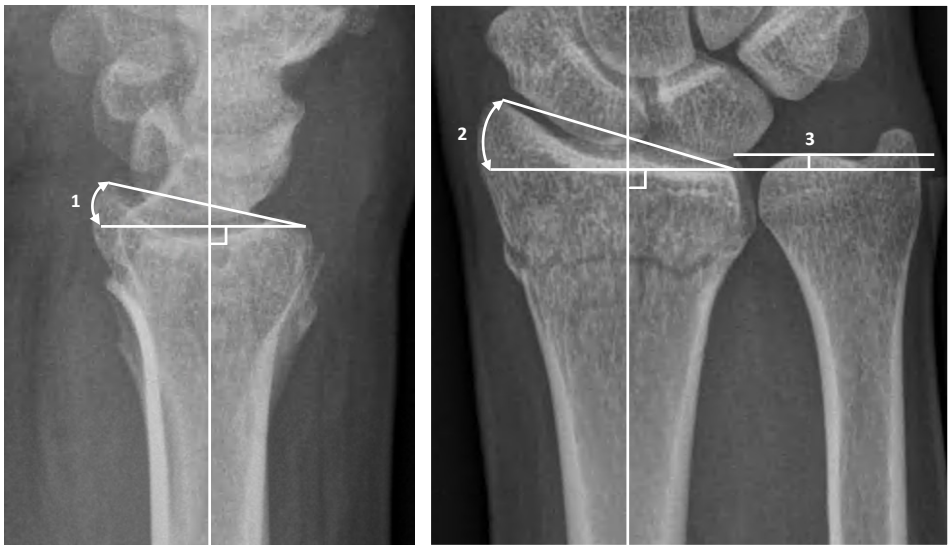

Figure 2. (1) Angulation on lateral radiograph (left), (2) inclination and (3) positive ulnar variance on posterior-anterior radiographs (right).

When one of these parameters is not within the guideline thresholds, a fracture is classified as "displaced". In cases where radiographs do not provide sufficient detail—especially for complex or intra-articular fractures or when intra-articular involvement is questioned—computed tomography (CT) scans offer enhanced imaging detail, supporting fracture classification and providing a more reliable view of articular involvement and displacement (5). Although some studies suggest that

additional CT imaging can improve treatment outcomes and decision-making, the evidence for its routine use remains limited (6-10). Consequently, its added value is open to debate, a topic further investigated in this thesis.

A DRF can range from a simple extra-articular isolated fracture to a complex multi-fragmented intra-articular fracture. These fractures are classified according to the AO/Orthopedic Trauma Association (AO/OTA) system, which distinguishes between Type A (extra-articular), Type B (partial intra-articular), and Type C (complete intra-articular) fractures (11). In complex fracture patterns of DRFs, the widely used AO/OTA classification system demonstrated limited inter-observer reliability (12-14). While detecting DRFs on radiographs is most often not a problem, classifying DRFs accurately using radiographs shows low interobserver agreement (13, 15). In recent years, artificial intelligence (AI) has shown promising potential for detecting and classifying fractures on radiographs (16-21). This thesis further investigates the implementation of AI for diagnosing and classifying DRFs.

Treatment and instability of distal radius fractures

Correct management of these fractures remains difficult. Treatment for DRFs varies, ranging from conservative approaches, such as cast immobilization, eventually preceded by closed reduction, to surgical intervention via open reduction and internal fixation (ORIF). In two-thirds of all DRFs, alignment is beyond the threshold, and closed reduction and cast immobilization are required (22). However, after closed reduction, around half of the DRFs re-displace in cast (23, 24). The terms "instability" and "re-displacement" imply that radiographic alignment has exceeded an acceptable threshold. Loss of threshold alignment includes deformities such as volar or dorsal angulation, loss of inclination, positive ulnar variance, or the occurrence of an intra-articular step-off or gap. If re-displacement occurs, surgical intervention is often needed to optimize outcome. Inadequately treated DRFs can result in malunion of the fracture in approximately 35% of the conservatively treated patients, compared to 10% of those undergoing surgical intervention. Malunion, defined as healing with malalignment can result in reduced grip strength, decreased wrist mobility, increased pain, and aesthetic concerns (25-27). Because re-displacement is often diagnosed one

or more weeks after trauma, delayed surgical intervention often results in unnecessary initial casting, a more complex surgical procedure, and potentially worse outcomes. Therefore, it will be highly beneficial if clinicians can predict instability immediately after trauma, allowing for timely decision-making and optimal treatment planning (24, 28, 29).

However, prediction of this fracture instability remains challenging (3). Little is known about the accuracy and reliability of imaging methods to predict DRF re-displacement. Prior evidence showed that factors associated with re-displacement include age, gender, amount of dorsal or volar comminution, ulnar variance, and dorsal angulation (30-35). Despite these findings, there is no consensus on whether and how the secondary displacement of DRFs can reliably be predicted. Data on the current predictive accuracy of healthcare professionals is lacking. Therefore, this thesis analyses the surgeons' ability to estimate the loss of threshold alignment of DRFs.

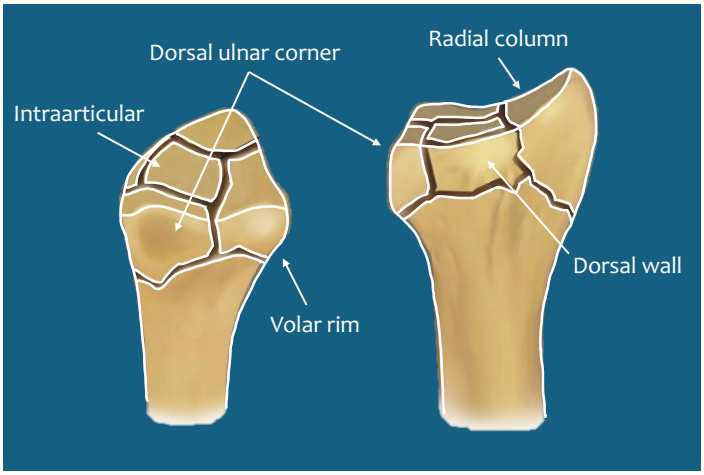

Figure 3. Fragment-specific classification by Medoff et al. (4)

While the use of solitary volar locking plates is the most common fixation method, (36, 37) some complex multi-fragmented fractures might need additional plating. Achieving stable fixation in highly comminuted fractures can be challenging due to limited bone purchase in main fragments and the need to avoid hardware complications (60-62). In highly comminuted fractures, Medoff presented a fragment-specific classification system with the styloid, volar rim, dorsal wall, dorsal-ulnar corner and intra-articular fragments (4) (Figure 3).

The most challenging fracture fragments, essential to address in the treatment, are small fragments of the radial styloid, volar ulnar corner, or dorsal ulnar corner (DUC) (4, 38).

Multiple studies have suggested that highly comminuted fractures often require additional dorsal or radial approaches for adequate visualization and fixation (39-42).

This is particularly the case in fractures involving the DUC fragment, which plays a crucial role in maintaining the stability of the distal radioulnar joint (DRUJ), the dorsal rim, and appropriate dorsal tilt (4, 43). Fixation of the DUC fragment can technically be demanding, and insufficient fixation can easily lead to radiocarpal subluxation or instability of the DRUJ (41, 44, 45). Surgeons often attempt to minimize the dorsal prominence of volar-placed screws to reduce hardware-related complications (46). To minimize the use of multiple plates and screws extending through the dorsal cortex in comminuted fractures, including an unstable DUC, this thesis evaluates a new method utilizing a volar locking plate combined with a dorsal bone clamp, functioning as a scaffold for fixation.

Complications of operative fixation of DRFs

The complications must be clearly understood by both surgeons and patients for accurate and comprehensive counseling in shared decision-making for the operative treatment of DRF. Complications associated with volar locking plates occur in up to 36% of cases, including nerve dysfunction, tendon injury and hardware complications. Other complications include wound infection, refracture or loss of reduction, mal- and nonunion and complex regional pain syndrome (47, 48). When these complications occur, hardware removal is often discussed. Previous studies report a wide variation in the incidence of hardware removal ranging from 0 to 100% and indications for hardware removal are not always clearly described (5, 47, 49-53). With the growing use of volar plates, it is plausible that the frequency of hardware removal may rise consequently. Despite this, longitudinal studies exploring trends in hardware removal over extended periods and the difference in indications are scarce. Therefore, the incidence of hardware removal after volar plate fixation over 10 years is studied in this thesis. These data might influence the counseling of patients for operative treatment of the distal radius and might be of interest from a management perspective.

Another significant but less common complication is DRF nonunion, occurring in 0.03%-1.6% of the cases (54). Nonunion is defined as the absence of bridging callus formed between the cortices of the fracture six months after surgery (55). Nonunion can result from mechanical factors following inadequate stabilization, poor fracture alignment, or implant failure. Additionally, severe bone comminution, infection and patient-related factors like smoking, osteoporosis and other comorbidities increase the risk of nonunion (56, 57). Even though the very rare occurrence of this complication, fracture nonunions can result in severe pain, functional limitations and substantial loss of hand and wrist function, needing a surgical intervention (55, 58). Treatment of nonunion might require revision surgery, involving re-ORIF combined with autografts, allografts or synthetic bone substitutes to restore alignment and achieve bony healing (56, 57). However, evidence of surgical outcomes after nonunion repair operations remains limited. Additionally, some patients require reoperation after surgical management of DRF nonunion. To address this knowledge gap, this thesis examines surgical outcomes by examining reoperations after nonunion repair operations and factors associated with these reoperations.

Ligamentous instability - Scapholunate interosseous ligament injury

Beyond the osseous structures of the wrist, including the distal radius, a complex ligamentous network is crucial for maintaining wrist stability. This network comprises both intrinsic and extrinsic ligaments, which secure the relationship between the carpal bones and the distal forearm. The intrinsic ligaments, particularly the scapholunate interosseous ligament (SLIL) and the triangular fibrocartilage complex (TFCC), are considered the primary stabilizers of the carpal region. The SLIL is considered the most critical intrinsic ligament for preserving carpal stability (59-62).

SLIL injury

Although fractures of the wrist's osseous components can lead to instability, wrist trauma frequently involves injuries to the intrinsic ligaments, particularly the scapholunate interosseous ligament (SLIL) (63). Notably, such ligamentous damage may arise from acute trauma but can also occur in repetitive stress or due to

inflammatory processes. When the SLIL is injured, dissociation between the scaphoid and lunate disrupts coordinated movement of the scapholunate joint, resulting in carpal instability. This biomechanical instability is the most common type of traumatic carpal instability and a significant source of pain and mechanical dysfunction (64-70). Diagnosing SLIL injuries relies on a combination of clinical evaluation, imaging and wrist arthroscopy. Clinically, patients often present with pain, swelling, and reduced grip strength (67). Painful palpation of the scapholunate interval, a painful finger extension test and a positive Watson shift test can be used to assess injury of the SLIL and scapholunate instability (71).

Standard radiographs, PA, lateral and clenched fist view, can reveal hallmark signs of SLIL injury, including widening of the scapholunate interval, scaphoid ring sign, and even a dorsal intercalated segment instability if secondary stabilizers fail. Additionally, a contralateral radiograph is recommended to account for anatomical variation and determine whether the SL distance is truly pathological (63, 69). Furthermore, magnetic resonance imaging (MRI) provides detailed visualization of ligamentous injuries and is also valuable for identifying other traumatic wrist pathology, such as TFCC injuries and chondral lesions (72, 73). Many patients do not recall the specific moment of trauma that led to the injury of the SLIL, making it difficult to indicate when an MRI of the wrist is necessary (59-62). Therefore, the prevalence of SLIL injury in patients who underwent wrist MRI for various indications, with or without recall of specific trauma and with or without clinical suspicion for SLIL injury, is further investigated in this thesis.

Primary and secondary wrist stabilizers

While the SLIL serves as the primary wrist stabilizer, the secondary stabilizers, comprising the extrinsic ligaments, include the volar long radiolunate ligament (LRL), volar short radio lunate ligament (SRL), volar radioscaphocapitate ligament (RSC), volar scaphoidtrapeziotrapezoid ligament (STT), dorsal radiocarpal ligament (DRC), and dorsal intercarpal ligament (DIC) (65, 66, 74, 75). See Figure 4. The relationship between injury to SLIL and the presence or absence of injury to the

extrinsic ligaments and their combined effect on carpal stability remains poorly understood (64-67). While previous research has explored the relationship between SLIL injuries and the dorsal extrinsic ligaments (DRC and DIC), the association between SLIL and volar extrinsic ligament injury in carpal stabilization is further investigated in this thesis (76-78).

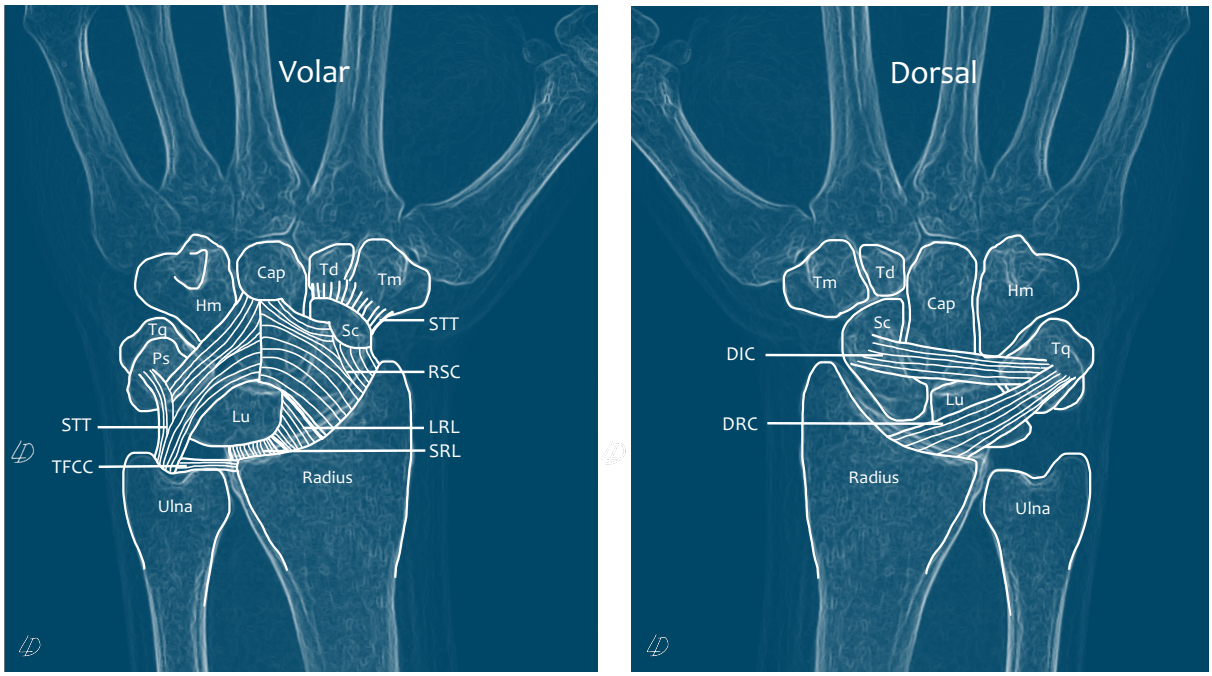

Figure 4. The volar (left) and the dorsal (right) capsular ligament of the wrist. Hm: Hamate; Cap, capitate; Td, trapezoid; Tm, trapezium; Tq: triquetrum; Ps: Pisiform; Sc: scaphoid; Lu: lunate; volar long radio lunate ligament (LRL), volar short radio lunate ligament (SRL), volar radioscaphocapitate ligament (RSC), volar scaphotrapezio trapezoid ligament (STT), dorsal radiocarpal ligament (DRC), and dorsal intercarpal ligament (DIC).

AIM AND OUTLINE OF THIS THESIS

Wrist instability is a complex and multifaceted condition that can arise from various underlying pathologies, including DRFs and SLIL injuries. Accurately diagnosing these conditions, standardizing treatment approaches, and optimizing patient outcomes remain challenging. This thesis aims to enhance the diagnostic accuracy of wrist instability, minimize variability in treatment strategies, and establish a foundation for more personalized and effective management.

Part I - Osseous instability in the wrist – distal radius fractures

Part I critically examines current diagnostic tools for assessing the severity and alignment of both stable and unstable DRFs.

Chapter 2 evaluates the value of an additional CT scan, compared to conventional radiographs, in alignment measurements of DRFs. Differences might shift a DRF from properly aligned to malaligned if the guideline threshold is passed. In addition, it explores the agreement and reliability of each imaging modality in measuring DRF alignment.

Chapter 3 gives an overview on the performance of AI on detection and classification of DRFs on conventional radiographs, and the comparison of this performance to human observers.

Chapter 4 & 5 consist of two scenario-based, randomized survey experiments, caried out separately, combined for publication. In **Chapter 4** surgeons estimated the likelihood of re-displacement in reduced DRFs on either pre- and post-reduction radiographs or on post-reduction radiographs alone. **Chapter 5** compares surgeons' estimations when only radiographs were provided versus radiographs supplemented by CT imaging. It also investigates whether specific patient factors affect these estimations. The study addresses the following questions:

- Can surgeons accurately estimate the loss of threshold alignment of reduced DRFs on radiographs?

- Can this estimation of loss of threshold alignment be improved by CT-scan, in addition to conventional radiographs?
- Are there any patient factors associated with this estimation of loss of threshold alignment of DRF?

Part II - Treatment and complications of distal radius fractures

Part II focuses on determining the most appropriate treatment strategies for unstable, multi-fragmented DRFs and analyzing the complications associated with surgical fixation.

Chapter 6 evaluates a proposed method using a volar locking plate combined with a dorsal bone clamp as a scaffold for fixation in multi-fragmented DRFs involving the distal ulnar corner (DUC) fragment. The following questions are addressed:

- Is fixation of the DUC fragment always necessary to maintain radiocarpal alignment and can an acceptable range of motion (ROM) be achieved when using a volar locking plate?
- Does screw purchase in the DUC fragment influence the maintenance of radiocarpal alignment and the ROM outcomes in patients with DRFs treated with volar plate fixation?
- Does the DUC fragment size matter for stabilization of an DRF with only a volar locking plate.

Chapter 7 describes the incidence of volar plate removal over 10 years. It investigates:

- Whether there has been increased volar plate removal for DRFs over the past decade.
- Changes in the reasons for hardware removal during this period.
- Patient-related factors associated with the risk of hardware removal.

Furthermore, **Chapter 8** examines both the incidence of reoperation after surgical management of DRF nonunion and the factors associated with these additional procedures.

Part III - Ligamentous instability in the wrist – scapholunate interosseous ligament injury

Finally, Part III addresses ligamentous instability of the wrist by examining the prevalence of SLIL injuries on MRI in patients with and without wrist trauma and assessing whether extrinsic ligament involvement contributes to scapholunate (SL) dissociation when the SLIL is injured.

Chapter 9 investigates the prevalence of SLIL signal changes in patients who underwent wrist MRI and aims to answer the following questions:

- What is the prevalence of SLIL signal changes in patients who underwent wrist MRI for various indications, including low or high clinical suspicion?
- What is the prevalence of SLIL signal changes in patients who underwent wrist MRI with or without prior wrist trauma?
- What are the factors associated with changes in the SLIL signal in these two groups?

Chapter 10 examines the association between the occurrence of extrinsic ligament injury and SL dissociation in patients with SLIL injury. The following questions are aimed to be answered:

- Is there an association between patients with SL injury and the occurrence of an SL diastasis and injury to the volar extrinsic ligaments?
- Is there an association between patients with SL injury and the occurrence of an SL diastasis and injury to the dorsal extrinsic ligaments?
- What is the inter-observer agreement of identifying injured intrinsic or extrinsic ligaments?

Part IV - General discussion and further perspectives

In **Chapter 11**, the results of this thesis are discussed, and future perspectives are given for the optimization of diagnosis, prediction and treatment for wrist instability including DRF and SLIL injury. **Chapter 12** presents a summary and conclusion of this thesis, as also it presents in Dutch.

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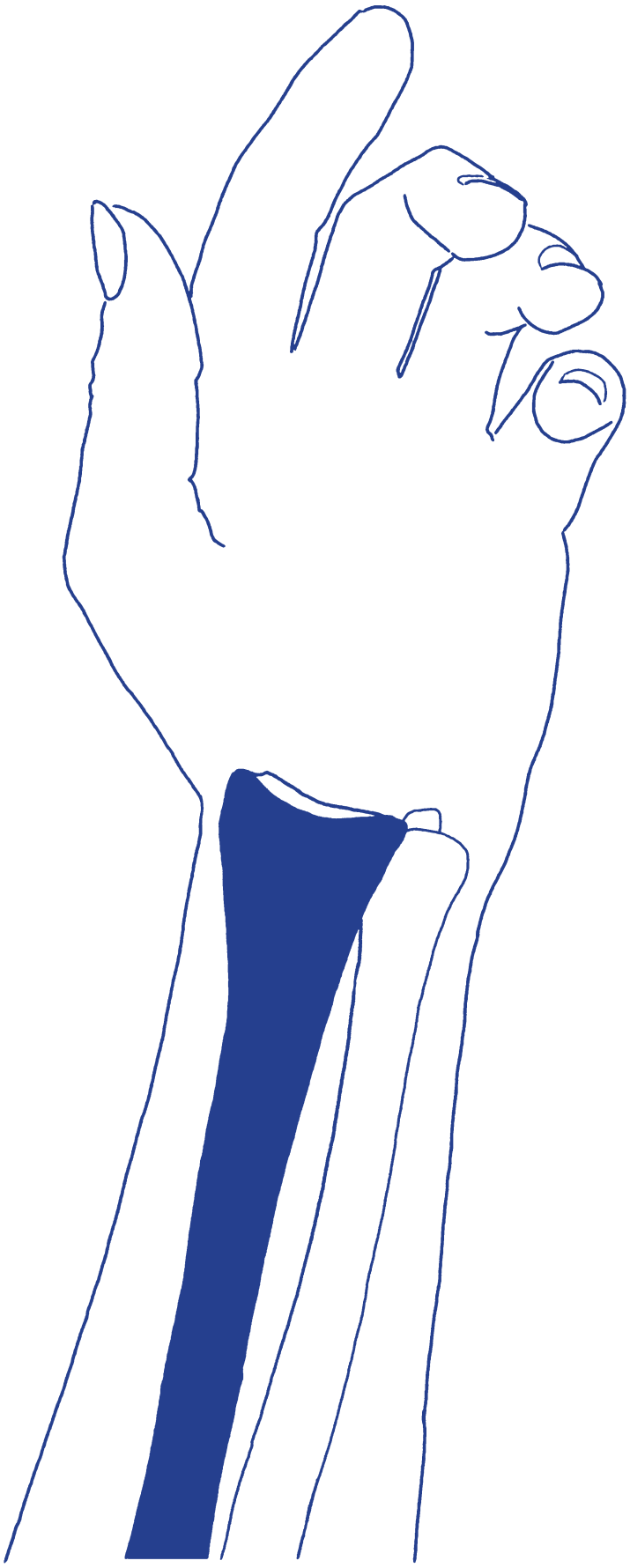


PART I

Osseous instability in the wrist
Distal radius fractures

Chapter 2

Traditional radiography versus computed tomography to assess reduced distal radius fractures

Chapter 3

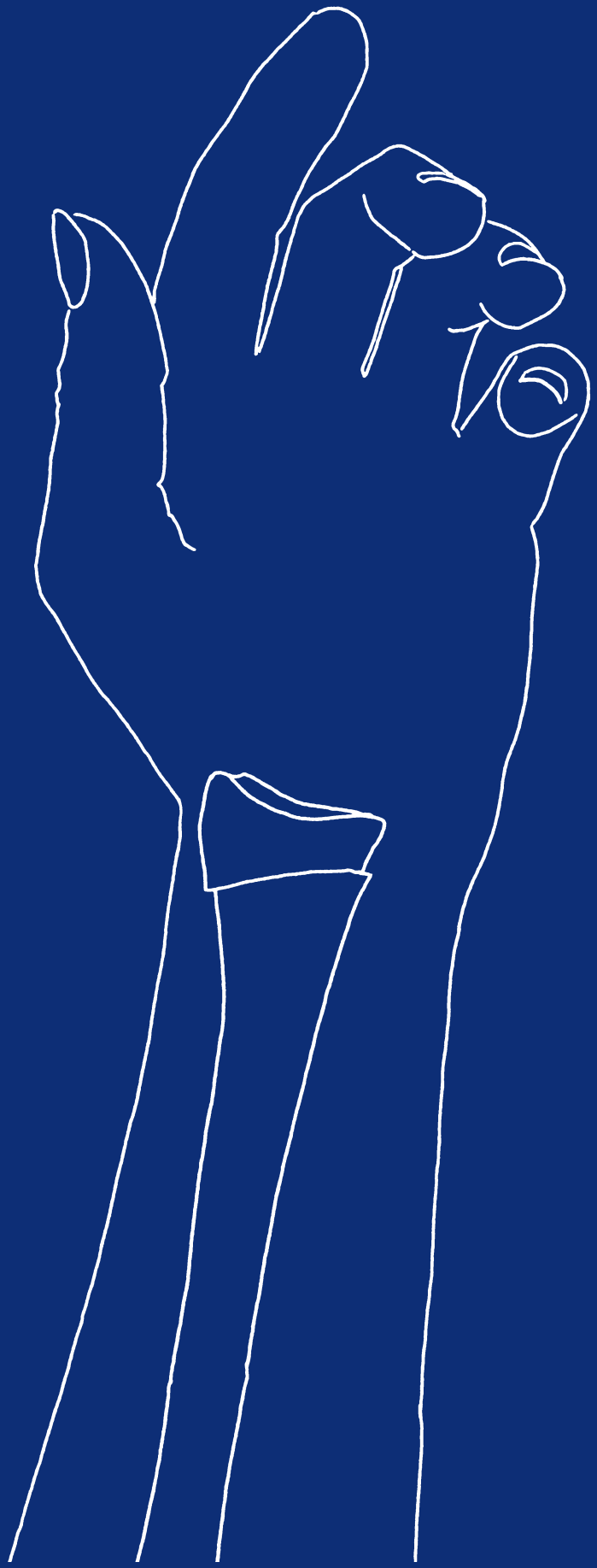
Artificial Intelligence for detection, classification and prediction secondary displacement of distal radius fractures on radiographs; a systematic review

Chapter 4

Can surgeons accurately estimate loss of threshold alignment (instability) of a distal radius fracture after closed reduction and cast immobilization?

Chapter 5

The prediction of loss of threshold alignment of distal radius fractures: does computed tomography increase accuracy and inter-observer agreement?



CHAPTER 2

Traditional radiography versus computed tomography to assess reduced distal radius fractures

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ABSTRACT

Introduction

This study compares computed tomography (CT) with plain radiography in its ability to assess distal radius fracture (DRF) malalignment after closed reduction and cast immobilization.

Methods

Malalignment is defined as radiographic fracture alignment beyond threshold values according to the Dutch guideline encompassing angulation, inclination, positive ulnar variance and intra-articular step-off or gap. After identifying 96 patients with correct alignment on initial post-reduction radiographs, we re-assessed alignment on post-reduction CT scans.

Results

Significant discrepancies were found between radiographs and CT scans in all measurement parameters. Notably, intra-articular step-off and gap variations on CT scans led to the reclassification of the majority of cases from correct alignment to malalignment. CT scans showed malalignment in 53% of cases, of which 73% underwent surgery.

Conclusion

When there is doubt about post-reduction alignment based on radiograph imaging, additional CT scanning often reveals malalignment, primarily due to intra-articular incongruency.

INTRODUCTION

Distal radius fractures (DRF) that heal non-anatomically could result in functional impairment in the short term and degenerative changes on the long run. Malalignment of a DRF is defined as radiographic fracture alignment beyond threshold parameters by the Dutch guidelines: ≥ 10° of dorsal angulation, or ≥ 20° of volar angulation, ≤ 15° of inclination, ≥ 3 mm of positive ulnar variance and ≥ 2 mm intra-articular step-off. The question of to which extent fracture displacement can be accepted remains open. Traditionally, fracture displacement is measured on plain radiographs, but the use of computed tomography (CT) scans to guide treatment has increased (1, 2). A CT scan has the potential to provide more details on the fracture alignment but is less easily available and more expensive, and radiation exposure is increased compared to plain radiographs. Therefore, it is relevant to determine in which specific cases a CT scan adds value to the radiographic parameters used to assess malalignment.

While radiographs are standardly used to determine the existence of a fracture (3-10), additional CT scanning is advised when doubting the alignment or involvement of the articular surface and consequently doubting the necessity for surgical reduction and fixation, according to the Dutch guidelines (11). Compared to conventional radiographs, additional CT scanning is more accurate in determining the degree of angulation and the involvement of the distal radioulnar joint (4, 12-14). The treatment choice is adjusted from conservative to operative in 23% to 46% of DRFs after additional CT scanning, and a CT scan improved the intraobserver reproducibility in the choice of surgical treatment (1, 2, 4, 12-20). However, most of these studies are based on relatively small sample sizes (1, 2, 16, 17, 19-21), evaluated by a limited number of observers, and not evaluating all five fracture characteristics (angulation, inclination, positive ulnar variance, step-off and gap) that are used to guide the treatment modality (11). Thus, the differences in assessment of all relevant fracture alignment characteristics, measured on radiographs versus CT scans in a large cohort, have yet to be investigated.

The aim of this study is to unravel whether an additional CT scan compared to conventional radiographs will result in different alignment measurements that might cross the border from correct to malaligned in DRFs. In addition, the agreement and

reliability between radiographs and CT scans are assessed, with a sub analysis to confound for secondary displacement.

METHODS

Study Population and Data Selection

According to the local Medical Ethics Committee approved protocol (MEC-2020-0258), cases were selected from a retrospective cohort. This cohort consists of patients who sustained a DRF and were presented at our academic level 1 trauma centre between January 2011 and July 2020. Inclusion criteria were: 1) age ≥ 18 years, 2) reduced DRF, 3) pre- and post-reduction posterior-anterior (PA) and lateral radiographs available, and 4) additional post-reduction CT scans available, taken within seven days after trauma. Exclusion criteria were: 1) no, incomplete or inadequate radiographic follow-up, 2) re-fracture of the distal radius, 3) malalignment post-reduction according to the Dutch Guidelines for DRFs (11), 4) fracture not reduced within 24 hours after trauma and 5) initial treatment with external or internal fixation.

Baseline and fracture characteristics

The following baseline characteristics were collected: age at the time of injury (years), sex, AO fracture classification (A/B/C, according to the trauma radiograph), the interval between trauma and additional CT scanning (days), and – in case of surgical reduction and fixation – the interval between trauma and surgery.

On all radiographs and CT scans, fracture alignment was measured to define whether the fracture was correctly aligned or not. The fracture characteristics that were measured DRFs comprise radial inclination (degrees), positive ulnar variance (mm) and intra-articular step-off and gap (mm) on PA views, and dorsal or volar angulation (degrees) and intra-articular step-off and gap (mm) on lateral views on radiographs (Figure 1A). Four trained and experienced researchers conducted these alignment measurements according to the same measurement guidelines by Medoff et al. (22). When doubting measurements, radiographs and CT scans were reviewed by a senior orthopaedic surgeon (JC).

Angulation was measured on the sagittal CT scan, on the slide where the line could be drawn between the uppermost (dorsal and volar) point of the articular surface of the distal radius (23, 24). Inclination and positive ulnar variance were measured on the coronal CT view, on the slide where the distal-most point of the radial

styloid and the midpoint between the dorsal and palmar radial cortical margins was shown (4) (Figure 1B). Intra-articular step-off or gaps were measured on the slide with the largest step-off or gap (4) (Figures 1A and B). Measurements were performed using a DICOM viewer, Synedra View Personal, version 20.0.0.4. In case of multiple step-offs or gaps, the largest was described. When a step-off or gap was measured on a CT and could not be seen on radiographs, it was valued as '0' on the radiograph.

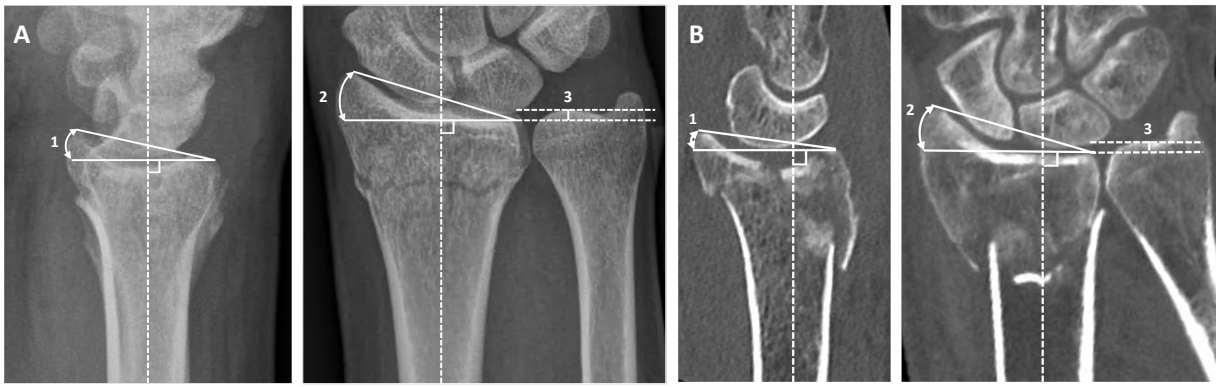


Figure 1. Examples of measurements on radiographs and CT scans: (1) Angulation, (2) inclination, and (3) positive ulnar variance on radiographs; B. (1) Angulation, (2) inclination, and (3) positive ulnar variance on CT scan.

Data presentation

The primary outcomes involved the difference in angulation, inclination, positive ulnar variance, intra-articular step-off, and gap on post-reduction radiographs and additional CT. We assessed each parameter individually to determine if correct alignment or malalignment was seen on CT. Overall, fractures were labelled for all imaging as correctly or malaligned according to the Dutch guideline threshold values. The Dutch guidelines for DRFs state that a fracture is malaligned when one or more of the following threshold values are exceeded: $\geq$ 10° of dorsal angulation, or $\geq$ 20° of volar angulation, $\leq$ 15° of inclination, $\geq$ 3 mm of positive ulnar variance and $\geq$ 2 mm intra-articular step-off (11). The median time between trauma and CT scan and the median time to surgical intervention was calculated. As a secondary outcome, the agreement between the two imaging techniques, radiographs versus CT, and the reliability of the agreement was calculated. In addition, a separate assessment was

performed on the subgroup, for which the CT scan was made the same day as the post-reduction radiographs to minimize the change for early secondary displacement.

Statistical analysis

Data distribution was assessed using the Shapiro-Wilk test, with a p-value <0.05 indicating non-normal distribution. Missing data were not imputed, and a p-value <0.05 was deemed significant for all analyses.

Descriptive statistics summarized patient characteristics and radiographic measurements. Continuous data are reported as mean with standard deviation (SD) for normal distributions or median with interquartile range (IQR) for non-normal distributions. Categorical data are presented as counts with percentages.

CT scan analyses included calculating percentages for correct alignment versus malalignment, with 95% confidence intervals (CIs) derived via the modified Wald method. Statistical significance was inferred when the 95% CIs did not encompass 0. The Wilcoxon Signed-Rank test evaluated differences in fracture alignment measured on radiographs and CT scans.

Agreement between imaging methods and their clinical relevance was examined through Bland-Altman analysis, plotting mean measurements against their differences. Points scattered above 0 with a 95% CI above 0 indicated that the CT scan measurements were larger than those on radiographs. This analysis, along with Intra Class Correlation (ICC) for reliability (categorized by Koo and Li, 2016 as "poor" <0.5, "moderate" 0.5-0.75, "good" 0.75-0.90, and "excellent" >0.90), highlighted systematic biases and agreement levels. Both analyses extended to acute CT scans.

RESULTS

Study population

We included 96 patients with 96 DRFs from our database from 2011 to 2020. A flowchart of the inclusion process is shown in Figure 2. Baseline characteristics are demonstrated in Table 1. According to the AO classification, most fractures concern AO type C (68%). The median interval from presentation at the emergency room to CT scanning was three days (IQR 2-4 days), and in 55% of cases, the CT scan was performed on the day of reduction. A total of 63 patients (66%) were treated surgically; the median time from trauma to surgical fixation was five days (IQR 3-9 days).

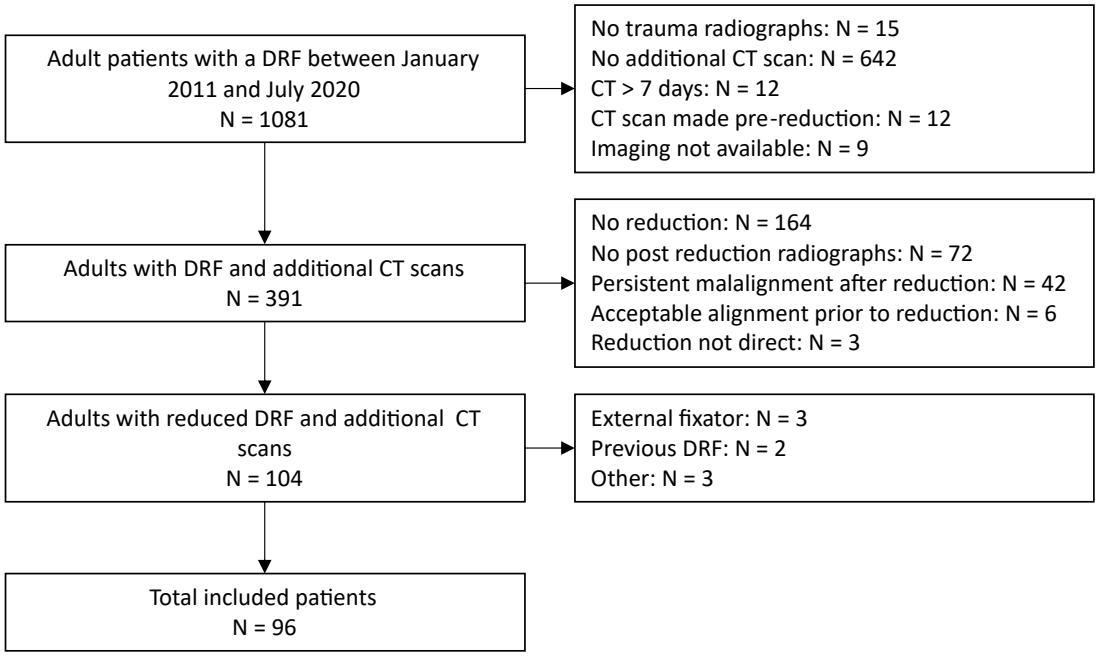


Figure 2. Flowchart of the study population. DRF: Distal radius fracture; CT: Computed tomography

Table 1. Baseline patient- and fracture characteristics.

Characteristic	N = 96
Age in years, mean (SD)	52 (SD 17.5)
Female, n (%)	60 (63%)
AO classification, n (%)	
A Extra-articular	19 (20%)
B Partial articular	12 (12%)
C Complete articular	65 (68%)

Primary outcome

The median measurements on all parameters differed significantly when comparing radiographs and CT scans (Table 2). Radiograph measurements and CT scans agreed that after reduction, 68 (71%) of DRFs were dorsally angulated and 28 (29%) volarly. In contrast with the acceptable sagittal angulation on radiographs, measurement on CT scan revealed unacceptably dorsal angulation in 20 (29%) patients and unacceptably volar angulation in 3 (11%) patients. Inclination was measured in all cases, revealing malalignment in 17 cases (18%), only indicated by CT scans. Positive ulnar variance was measured in 36 (38%) cases, of which in 3 (8%) cases, a positive ulnar variance ≥ 3mm was measured on CT only. An intra-articular step-off or gap was measured in 28 (29%) and 76 (79%) DRFs, respectively, resulting in malalignment in 20 (71%) and 69 (91%) of the cases on CT.

In 53% of cases, the fracture was labelled correctly aligned on post-reduction radiographs, while additional CT scanning revealed a malalignment. In the other cases (47%), there was an agreement on both radiographs and CT scans on correct fracture alignment. Divided by fracture morphologies according to the AO classification (A/B/C), CT scans revealed malalignment in 52%, 41%, and 58% of the cases, respectively. The DRF was surgically treated in 73% of cases in which radiographs and CT disagreed. The remaining 27% with malalignment conform CT scan measurements were conservatively treated. In addition, surgery was chosen in 13% of DRFs that were correctly aligned conform the guideline. The number needed to treat (NNT), or as in this study, 'the number needed to diagnose', was 1.89. This indicated that approximately two patients would need to be assessed using CT scans instead of radiographs to correctly identify one additional case of malalignment that was misdiagnosed by radiographs.

Table 2. Fracture alignment measured on post-reduction radiographs and CT.

	Cases n = 96	Post-reduction alignment on radiographs	Post-reduction alignment on CT-scan	P-value[b]	Malalignment conform CT imaging[c]
Angulation					
Dorsal, °	68 [a]	5.0 (2.0–8.0)	6.0 (3.5-11.0)	**0.002**	20 (29%, 0.19-0.42)[d]
Volar, °	28 [a]	6.0 (1.0-10.8)	8.5 (3.3-14.0)	**0.015**	3 (11%, 0.03-0.28)[d]
Inclination, °	96 [a]	22.0 (18.0-23.7)	20.5 (17.0-23.0)	**0.016**	17 (18%, 0.11-0.27)[d]
Positive ulnar variance, mm	36 [a]	1.7 (1.0-2.0)	2.1 (1.5-2.4)	**0.007**	3 (8%, 0.05-0.30)[d]
Step-off, mm	28 [a]	1.0 (0.0-1.6)	2.1 (1.5-2.3)	**<0.001**	20 (71%, 0.51-0.86)[d]
Gap, mm	76 [a]	1.4 (1.0-2.0)	4.1(2.4-5.8)	**<0.001**	69 (91%, 0.81-0.95)[d]

If not noted differently, information is presented as median with interquartile range between parentheses.

[a.] Includes the number of DRFs in which this fracture parameter was measured.

[b.] Wilcoxon Rank Sum test was used.

[c.] Number of cases in which fracture alignment was not acceptably aligned on the CT scan.

[d] The 95% confidence intervals were calculated using the modified Wald method.

Secondary outcome

The agreement and reliability for all measurements between radiographs and CT scans were calculated (Table 3). Figure 3 shows the Bland-Altman plots assessing the agreement, showing that the differences vary systematically for all measurements. CT scans showed significantly increased angulation severity, loss of inclination, positive ulnar variances and intra-articular incongruences (Figure 3).

The intraclass correlation (ICC), which indicates reliability between the two imaging techniques, showed that the radiographs and CT scans were in poor agreement for all alignment measurements. The ICC also showed poor reliability for all measurements (Table 3).

In 55% of the included cases, the CT scan was obtained immediately after reduction. The separate ICC and Bland-Altman analysis for these cases showed differences in angulation, inclination, step-off and gap measurements. Only measurements of positive ulnar variance showed a negative ICC and did not vary systematically on the Bland-Altman plots (Table 4 and Figure 4).

Table 3. Correlation between alignment measurements performed on radiographs versus CT-scan.

	Cases N = 96	Intraclass Correlation[b]	95% Confidence Interval	Reliability
Angulation, °				
Dorsal	68[a]	0.19	-0.03-0.40	Poor
Volar	28 [a]	0.35	0.01-0.63	Poor
Inclination, °	96 [a]	0.44	0.26-0.59	Poor
Positive ulnar variance, mm	36 [a]	0.05	-0.23-0.34	Poor
Step-off, mm	28 [a]	0.11	-0.09-0.37	Poor
Gap, mm	76 [a]	0.09	-0.07-0.27	Poor

[a.] Includes the number of DRFs in which this fracture parameter was measured.
[b.] Type A intraclass correlation coefficients using an absolute agreement definition. Values < 0.5 indicates poor reliability.

Table 4. Sub analysis for correlation between alignment measurements on radiographs versus CT-scan, performed on same day.

	Cases N = 53	Intraclass Correlation[b]	95% Confidence Interval	Reliability
Angulation, °				
Dorsal	42 [a]	0.15	-0.12-0.42	Poor
Volar	11 [a]	0.27	-0.16-0.69	Poor
Inclination, °	53 [a]	0.52	0.30-0.69	Poor
Ulnar positive variance, mm	14 [a]	-0.03	-0.27-0.30	Poor
Step-off, mm	16 [a]	0.11	-0.10-0.43	Poor
Gap, mm	44 [a]	0.11	-0.08-0.33	Poor

[a.] Includes the number of DRFs in which this fracture parameter was measured.
[b.] Type A intraclass correlation coefficients using an absolute agreement definition. Values < 0.5 indicates poor reliability.

Figure 3. Bland-Altman Plots of the differences between radiographs versus CT scans. The CT measurements were subtracted from radiograph measurements. Horizontal black lines display the limits of agreement (95% CI). Points scattered above 0 with a 95% CI above 0 (red line) indicated that the measurements on the CT scan were larger than the measurements on radiographs.

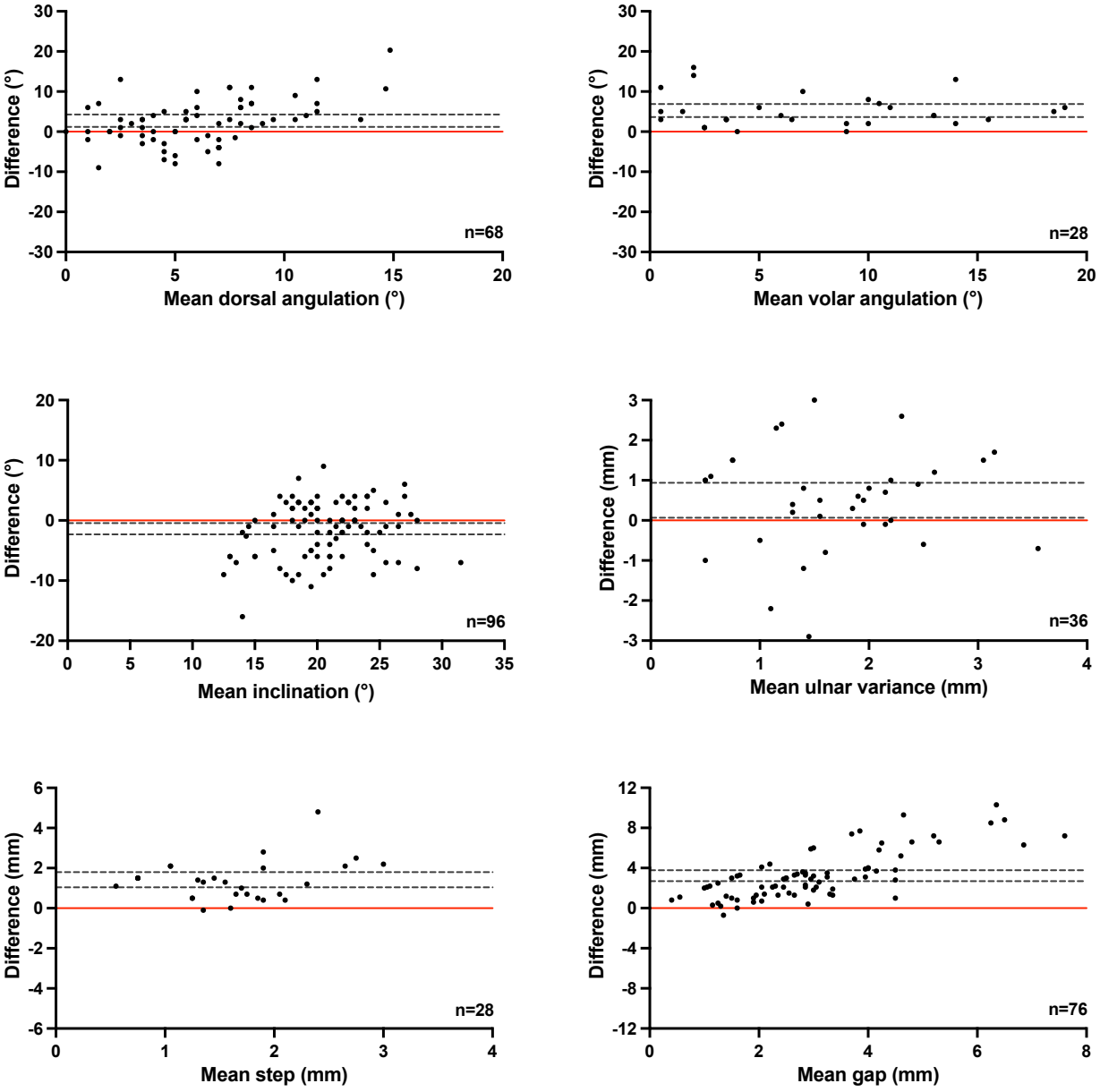
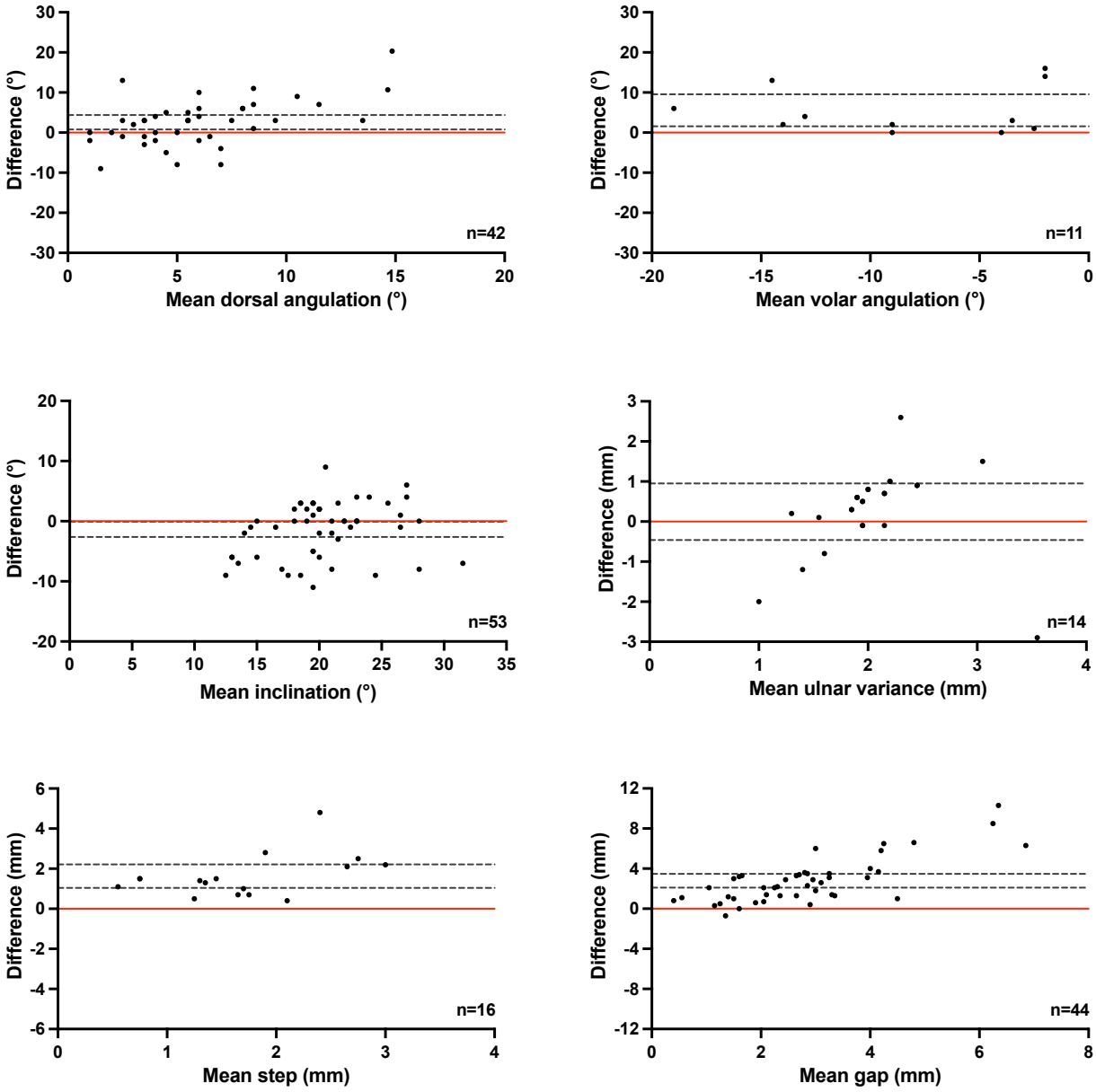


Figure 4. Sub analysis of radiographs versus CT scans made on the same day. Bland-Altman Plots of the differences between radiographs versus CT scans. The CT measurements were subtracted from radiograph measurements. Horizontal black lines display the limits of agreement (95% CI). Points scattered above 0 with a 95% CI above 0 (red line) indicated that the measurements on the CT scan were larger than the measurements on radiographs.



DISCUSSION

This study shows that conventional radiographs consistently underestimate reduced DRFs' severity compared to CT scans based on volar and dorsal angulation, loss of inclination, positive ulnar variance and intra-articular incongruence. In 53% of cases, additional CT scanning showed malalignment, while they appeared correctly aligned based on radiograph measurements. The ICC and Bland-Altman plots showed a clear discrepancy between the two imaging techniques on all measurement parameters, whereas CT scans showed significantly increased severity on all alignment measurements compared to radiographs.

In line with our findings, previous studies reported that radiographs tend to underestimate intra-articular incongruence concluding that the CT scan is more reliable for the measurement of intra-articular involvement in DRFs (4, 12-15). Furthermore, previous research has shown that CT scans increase inter-surgeon agreement on the need for surgical intervention (2, 14-18). Additional CT scanning changes the indication from conservative treatment to surgery in 23% to 46% of cases (2, 15, 19, 21). Therefore, in cases of uncertainty regarding the alignment after reduction, especially concerning the intra-articular incongruence, a CT scan may offer additional value. Future studies need to assess if this consideration would contribute to eventually improved clinical outcomes.

Although the Dutch guideline for DRFs advises operative treatment for malaligned fractures (11), approximately a quarter of malaligned DRFs in this cohort were treated conservatively. Potential reasons can be patient-related (e.g., age or concomitant health problems being a risk for surgery in general), fracture-related (e.g., alignment was close to threshold values), or surgeon-related (e.g., reluctance to operate on severely comminuted fractures). Due to the retrospective nature of this study, the exact reasons for the chosen treatment modality remain unknown.

Before advocating surgical intervention to prevent malunion, one has to realize that previous studies showed a poor correlation between malunion and clinical outcomes, especially in older patients (11). Studies report malunion rates of 35% in non-surgically treated fractures and 10% in surgically treated fractures (25, 26). Malunion might result in chronic pain, reduced function, decreased grip strength and

impaired ability to perform daily activities (27-29). Secondary invalidating osteoarthritis can also be initiated due to uneven force distribution across the radiocarpal joint surface (30). Further studies are needed to accurately determine the level of malalignment that leads to clinically unacceptable outcomes.

We decided to define the acceptability of fracture alignment conform the Dutch guidelines for DRFs. Simply because retrospective cases were used that were treated conform this guideline. Secondly, the Dutch guideline comprises a broad assessment of alignment. Volar angulation and inclination are not encountered in the American Academy of Orthopaedic Surgeons guidelines (31). However, both guidelines agree on the threshold values for dorsal angulation, positive ulnar variance, and step-off or gap. Our analysis revealed that shifts from correct to malalignment primarily occurred in measurements step-off or gap, parameters recognized by both guidelines.

This study needs interpretation in light of its strengths and limitations. To date, this study is the first to evaluate all these characteristics on radiographs and CT scans based on a large cohort of DRFs. Previous studies either only assessed intra-articular involvement (4, 14, 15) or only the extra-articular radiographic parameters (17). Furthermore, we consciously chose only to include cases in which the CT scan was made shortly after (within seven days) reduction. Additionally, the subgroup analysis on cases where the CT scan was performed immediately after reduction, which minimized the risk of secondary displacement, showed similar results. Therefore, it can be concluded that the discrepancies between the radiograph and CT are not attributed to secondary displacement.

As the first limitation, there was a potential for selection bias. According to the guidelines, a CT scan is made when doubting the alignment of a DRF and for pre-operative planning. Due to the retrospective design of this study, the exact reason behind the physician's decision to perform a CT scan is unknown. Therefore, conclusions should be carefully interpreted and are only applicable on cases in which post-reduction fracture alignment is doubted. Secondly, the measurements were not repeatedly executed by different observers, which might have resulted in undetected measurement errors. Consequently, inter- and intra-observer reliability of

measurements is not presented. However, Watson et al. showed that the intra-observer reliability is high for angulation measurements and moderate for inclination and positive ulnar variance measurements on radiographs (32). Lastly, in some cases, it was difficult to determine the axis of the radius on CT scans due to the truncation of the radial shaft. This might have influenced the angulation and inclination measurements since these are based on the radial shaft axis. However, the suboptimal radiology results depict more of the daily clinical situation than the optimal scientific situation, enabling extrapolation of the results.

This study suggests that additional CT scanning often shows DRF malalignment. According to our findings, the differences between radiographs and CT scans on step-off and gap measurements might have clinical implications because these measurements appeared beyond the guideline's threshold in 71% and 91% of the cases, respectively. In patients with any uncertainty about the articular congruency, a CT scan can provide valuable insights into fracture alignment. Therefore, a CT scan might help to plan a surgical approach. However, it is essential to consider the additional costs and the radiation exposure associated with additional CT scans, while the clinical impact remains unknown. Future research should assess the cost-benefits of additional CT scans of reduced DRFs. Furthermore, it should be taken into account that DRF treatment is not only based on radiological parameters. More aspects of the patient's condition and preferences should be considered when deciding on the optimal treatment for a DRF.

In conclusion, our study consistently demonstrates an underestimation of DRF alignment on radiographs compared to CT scans. According to the guideline, this leads to a shift from correct alignment to malalignment in over half of the cases, mainly underestimating intra-articular step-off and gap measurements. Our finding emphasizes the clinical significance of incorporating CT scans in evaluating and managing displaced DRFs in which post-reduction alignment is doubted. Further evaluation is needed to assess the effect of the implications of these findings, and it is essential to extend our focus on the importance of patient preferences beyond radiographic parameters.

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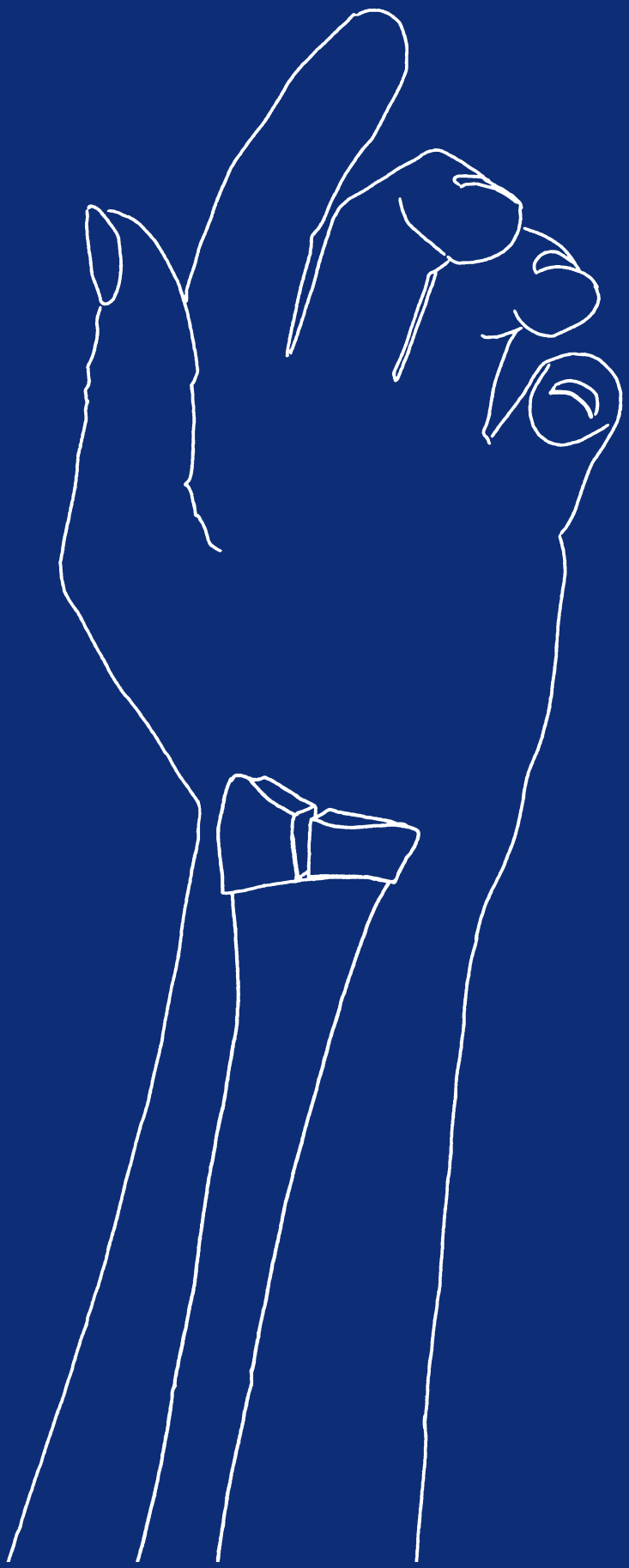

CHAPTER 3

Artificial Intelligence for detection, classification and prediction secondary displacement of distal radius fractures on radiographs; a systematic review

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ABSTRACT

Purpose

Early and accurate assessment of distal radius fractures (DRFs) is crucial for optimal prognosis. Identifying fractures likely to lose threshold alignment (instability) in a cast is vital for treatment decisions, yet prediction tools' accuracy and reliability remain challenging. Artificial intelligence (AI), particularly Convolutional Neural Networks (CNNs), can evaluate radiographic images with high performance. This systematic review aims to summarize studies utilizing CNNs to detect, classify, or predict loss of threshold alignment of DRFs.

Methods

A literature search was performed according to the PRISMA. Studies were eligible when the use of AI for the detection, classification, or prediction of loss of threshold alignment was analyzed. Quality assessment was done with a modified version of the methodologic index for non-randomized studies (MINORS).

Results

Of the 576 identified studies, 15 were included. On fracture detection, studies reported sensitivity and specificity ranging from 80% to 99% and 73% to 100%, respectively; the AUC ranged from 0.87 to 0.99; the accuracy varied from 82% to 99%. The accuracy of fracture classification ranged from 60% to 81% and the AUC from 0.59 to 0.84. No studies focused on predicting loss of thresholds alignment of DRFs.

Conclusion

AI models for DRF detection show promising performance, indicating the potential of algorithms to assist clinicians in the assessment of radiographs. In addition, AI models showed similar performance compared to clinicians. No algorithms for predicting the loss of threshold alignment were identified in our literature search despite the clinical relevance of such algorithms.

INTRODUCTION

The use of Artificial Intelligence (AI) to perfectly detect and classify fractures on radiographic images and to predict the best treatment option is considered a holy grail. This is also true for distal radius fractures (DRFs), where surgery aims to prevent losing threshold alignment (also known as a fracture being 'unstable') after closed reduction. The terminology might be confusing, as "fracture instability" and "fracture redisplacement" are often used interchangeably with "loss of threshold fracture alignment"; they are, however, insufficient and should be avoided where possible.

Detection of DRFs is most often not an issue, but non-displaced fractures or more subtle fracture lines, such as a radial styloid fracture, can be missed. (1) It has been noted that four out of five diagnostic errors made in the emergency department are missed fractures, and about 13-17% of missed fractures are located in the wrist. (2, 3) AI could be of great help here in aiding physicians.

DRF classification should 1) enable a standardized method to describe fractures and give guidance in the proper treatment per classification, 2) provide a consistent method of recording in the electronic patient system for evaluation of the patient in research, and 3) help compare studies using the same classifications and therefore optimize the treatment protocols. Considering this, a reliable fracture classification system can provide insight into clinical decision-making. (4) Therefore, a fracture classification tool without inherent surgeon bias is of interest.

When a DRF is displaced, closed reduction and cast immobilization are traditionally chosen. (5) However, secondary displacement occurs in up to 64% of the patients. (6) Identifying fractures likely to lose threshold alignment could greatly help clinical decision-making between nonoperative and surgical treatment. However, the accuracy and reliability of current fracture loss of threshold alignment prediction tools still need to be improved (7-10).

AI can execute tasks that humans previously performed. Specifically, Convolutional Neural Networks (CNN), which can evaluate visual input, have been of interest. (11) While earlier AI methods have led to applications with subhuman performance, recent CNNs can match and even surpass the capacity of humans to detect certain fractures on radiographs, focusing on isolated fracture types per

model. (12-16) The strength of computers and algorithms is their ability to perform many calculations rapidly, consistently and without exhaustion. CNNs can be used to implement automated fracture detection, classification, and prediction algorithms to guide clinicians in clinical and emergency settings. There has been less focus on using CNNs as a prediction tool, even though this might be the most valuable attribution for treatment decisions. Given the above-mentioned challenges within the care for DRFs and the promising development of AI, we conducted a systematic review to give an overview of studies using CNNs with radiographs to detect, classify, and/or predict loss of threshold alignment of DRFs. This study aimed to answer two questions: 1) What is the accuracy of current CNNs in detecting and classifying DRFs and predicting their loss of threshold alignment on radiographs? 2) Does the use of CNNs outperform the diagnostic performance of clinicians?

METHODS

Article selection, quality assessment, and data extraction

The systematic literature search was performed according to the PRISMA statement (17) and conducted in Medline ALL, Embase, Web of Science Core Collection, Cochrane Central Register of Controlled Trials and Google Scholar (100 top-ranked) in January 2024. The search strategy can be found in Appendix 1. This review was not registered online.

After removing duplicities, two authors (LHMD and KDON) independently screened the title and abstract for potential inclusion. Subsequently, a full-text review was done on the remaining articles with the defined inclusion and exclusion criteria. Articles were included if they described the use of CNNs to detect or classify DRFs or to predict loss of threshold alignment of DRFs on plain radiographs. Papers describing studies in children, reviews, letters, conference abstracts, surgical techniques, studies using robots, animal and cadaveric studies, non-orthopaedic fractures, and studies not published in English or Dutch were excluded. The inconclusive inclusion of articles was discussed afterward by the two reviewers. Covidence (Veritas Health Innovation, Melbourne, Australia) was used for the screening process and full-text review.

To assess the quality of the included articles, two reviewers (KDON, JW) independently used a modified version of the methodologic index for non-randomized studies (MINORS). A third reviewer was consulted if the scoring was inconsistent (LHMD). Studies with low scores on three or more items were excluded. Standardized forms were used to extract and record data (Microsoft Excel Version 16.21; Microsoft Inc, Redmond, WA, USA).

Outcome measures

The primary outcome was the performance of the AI model used, given in sensitivity, specificity, accuracy, Area Under the Receiver Operator Characteristics Curve (AUC), F-1 score, and average precision when present. The secondary outcome was comparing the AI models' performance to clinicians' performance. The highest possible F1-score is 1.0, indicating perfect precision and recall, and the lowest possible value is 0. The AUC is a score to measure the ability of a classifier to distinguish

between classes. Scores lie between 0.5 (classifier equal to chance) and 1 (a perfect classifier), scores <0.5 are not reported as they predict the wrong result. Average precision 50 (AP50) is a metric for localizing objects, meaning there is a 50% overlap between the object predicted by the algorithm versus the golden standard.

From each included article, the following data points were collected: author, year of publication, type of CNN model used, radiographic views, output classes, ground truth label assignment, number of patients or radiographs, performance metric (e.g. sensitivity, specificity, accuracy), comparison of CNN versus radiologist or reports, whether external validation was performed and potential open access availability of the model (Table 2). The reported output classes include DRF detection (fracture yes/no), localization and classification.

Quality appraisal

In this study, the MINOR Criteria included the following items: disclosure, input features, ground truth, external validation, performance metric, and AI model (Table 1). Disclosure was reported in almost all the studies except Suzuki et al. (18). All studies clearly described the study aim. Eight studies did not describe the input features used (15, 19-25). Five studies (19, 22-25) did not specify the ground truth used as a reference standard for the AI model. The external validation method was described only in six studies (13, 15, 26-29). Two studies (23, 24) did not describe the performance metric assessed in the studies. All studies described which AI model was used. According to the outcomes of the MINORS criteria, five studies were excluded because three or more criteria were missing.

Statistical analysis

If possible, a meta-analysis will be performed. If not possible due to the variance in utilized algorithms, an overview will be given, describing the number of patients or radiographs used in training and (internal or external) validation, accuracy, sensitivity, specificity, AUC, F-1 score, average precision, and Youden index when present.

RESULTS

Included studies

The literature search resulted in a total of 576 articles; after removal of duplicates, 365 abstracts were screened. Forty-six studies were full-text screened, and after quality assessment, eighteen studies were included in this review. (Figure 1). No new eligible studies were identified through reference lists.

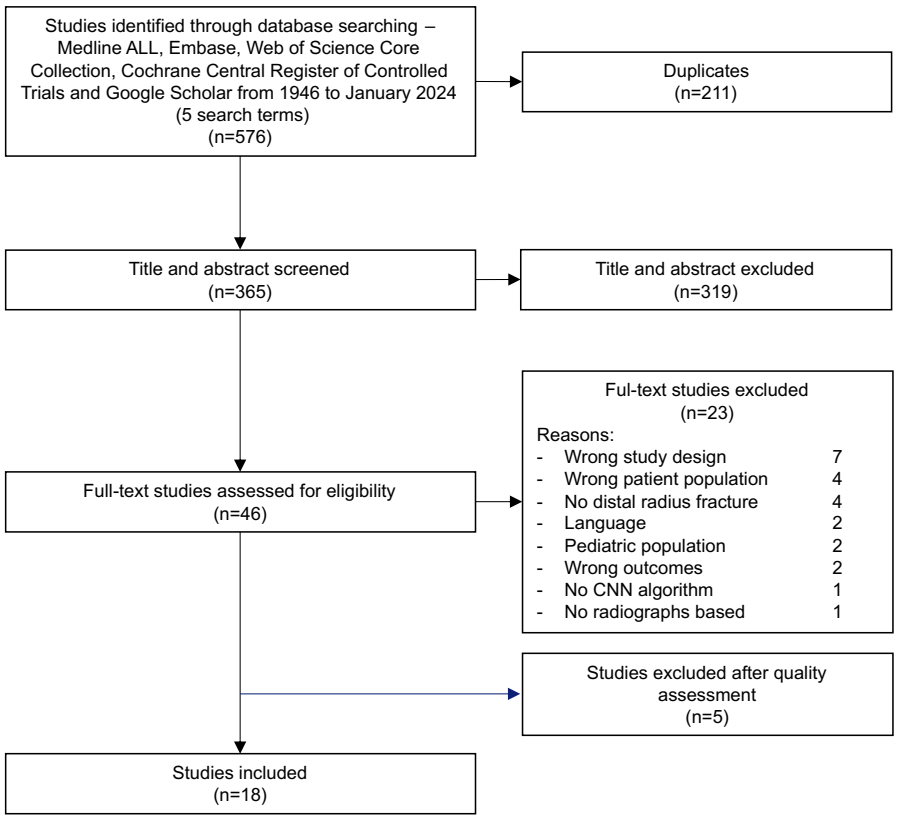

Figure 1. Inclusion and exclusion flowchart

Description of studies

Of the included studies, fourteen studies described detection (15, 18, 20, 26, 28, 30-38), one study both detection and classification (29), two studies both detection and localization (13, 21) and one study localization and classification (39) of DRFs. No studies on the prediction of loss of threshold alignment were found. Four studies used posterior-anterior (PA) and lateral radiographs (15, 32, 36, 40), in five studies anterior-posterior (AP) and lateral (18, 28-30, 38), and in three studies (26, 34, 37) an extra

oblique projection was used. Three studies only used lateral (33), AP (31), or PA (39) radiographs, and in three studies (20, 21, 35), the projection was not clearly described. As the ground truth, fifteen (15, 18, 20, 21, 26, 28, 29, 31-33, 36-40) studies used one or more radiologists' or surgeons' expertise to detect DRF. In addition, one study (34) used the radiological reports, checked and verified by a radiology registrar competent, and one study (30) used the clinical diagnosis of orthopaedic surgeons. In one study (35), the ground truth was not reported. The number of included radiographs ranged from 221 (21) to 31490 (15) and from 32 (21) to 3500 (15) for training and testing sets, respectively. Validation sets were used in six studies (15, 20, 21, 26, 28, 30), ranging from 54 (20) to 1461 (28) radiographs. The total number of fractures on the radiographs used in the studies ranged from 221 (21) to 4452 (34) DRFs.

Detection

The sensitivity of fracture detection was reported in fourteen studies (15, 18, 22, 26, 28, 30-35, 37, 38, 40), ranging from 80% (13) to 99% (18). Specificity was also reported, from 73% (28) to 100% (13, 18). The AUC was reported in twelve studies (15, 18, 27, 28, 30-33, 36, 37, 40, 41) ranging from 0.87 (13) to 0.99 (30). The accuracy was reported in nine studies (18, 29, 31, 32, 34, 35, 37, 38, 42) ranging from 82% (22) to 99% (18). In addition, Raisuddin et al. (36) reported a balanced accuracy of 76%. See Table 2.

Two CNN models were compared by Kim et al. (34), where the sensitivity, specificity, AUC and accuracy were similar for both models. Lindsey et al. (15) reported the performance of different test sets separately, where the AUC was 0.97, 0.98, and 0.99 for the internal, external, and clinical data test sets, respectively.

Classification

Two studies reported the performance of the classification of DRFs (29, 39). The AUC assessed separately by Tobler et al. (29) on fragment displacement, joint involvement, and detection of multiple fractures was 0.59, 0.68, and 0.84, respectively. The accuracy was 60%, 64% and 78%, respectively (29). Min et al. reported an AUC of 0.82, accuracy of 81%, sensitivity of 83%, specificity of 72% and a F1-score of 0.86.

AI versus clinicians

Among the included studies, eight (15, 18, 26, 29, 31, 36, 37, 40) compared the performance of AI and clinicians' performance. According to Blüthgen et al. (40), radiologists' performance was comparable to internal data and better on external data. Cohen et al. (26) found AI sensitivity significantly higher than initial radiology reports (IRR), with combined AI and IRR showing even greater sensitivity. Gan et al. (31) demonstrated that AI outperforms radiologists in accuracy, sensitivity, specificity, and Youden index. Comparisons with orthopaedic surgeons showed similar results. Lindsey et al. (15) revealed comparable sensitivity and AUC of aided and unaided emergency medicine clinicians by CNN. Notably, the model showed higher specificity compared to unaided clinicians. Raisuddin et al. (36) showed higher radiologist performance in normal cases and similar performance in hard cases.

Suzuki et al. (18) showed equal to better accuracy, sensitivity and specificity of CNN versus orthopaedic surgeons, though without statistically significant differences.

In Lee et al. (37), the sensitivity, specificity, accuracy, and AUC of two reviewers aided by AI increased in all fields compared to unaided. In addition, this study showed a decrease in mean interpretation time when aided by AI. Lastly, Tobler et al. (29) reported higher AUC for radiology residents than AI's assessment of DRFs without osteosynthetic material or cast.

Table 1. Quality assessment according to adapted MINORS criteria

Study type	Author, year	Dis-closure	Study aim	Input features	Ground truth	External validation method	Performance metric	AI model	Included / Excluded
Detection	**Antilla et al., 2022**	1	1	1	1	0	1	1	Included
Detection and localization	**Bluthgen et al., 2020**	1	1	1	1	1	1	1	Included
Detection	**Cohen et al., 2022**	1	1	1	1	1	1	1	Included
Detection	**Ebsim et al., 2019**	1	1	0	0	0	1	1	Excluded
Detection and localization	**Yahalomi et al., 2018**	1	1	0	0	0	0	1	Excluded
Classification	**Yang et al., 2021**	1	1	0	0	0	0	1	Excluded
Detection	**Gan et al., 2019**	1	1	1	1	0	1	1	Included
Localization	**Hardalac et al., 2022**	1	1	0	1	0	1	1	Included
Detection	**Javed et al, 2023**	1	1	0	0	0	1	1	Excluded
Detection	**Joshi., 2022**	1	1	0	1	0	1	1	Included
Detection	**Kim, 2018**	1	1	1	1	0	1	1	Included
Detection	**Kim et al., 2021**	1	1	1	1	1	1	1	Included
Detection	**Lee et al, 2023**	1	1	1	1	0	1	1	Included
Detection	**Lindsey et al., 2018**	1	1	0	1	1	1	1	Included
Localization and classification	**Min et al, 2023**	1	1	1	1	0	1	1	Included
Detection	**Oka et al., 2021**	1	1	1	1	0	1	1	Included
Detection	**Raisuddin et al., 2021**	1	1	1	1	0	1	1	Included
Detection	**Rashid et al., 2023**	1	1	0	0	0	1	1	Excluded
Detection	**Suzuki et al., 2022**	0	1	1	1	0	1	1	Included
Detection	**Thian et al., 2019**	1	1	1	1	1	1	1	Included
Detection and classification	**Tobler et al., 2021**	1	1	1	1	1	1	1	Included
Detection	**Ureten et al., 2022**	1	1	1	1	0	1	1	Included
Detection	**Zhang et al. 2023**	1	1	1	1	0	1	1	Included

Table 2. Description of studies

Author, year	Study type	AI models used (type)	Projection of radiograph	Output classes	Ground truth label assignment	N of radiographs (n of fractures)	External validation	Performance metrics	Performance outcomes	Comparison CNN vs. radiologist	Open access
Antilla et al., 2022	Detection	DL: U-Net	PA and lateral	Two (fracture yes/no)	3 hand surgeons	Trained: 6948 Tested: 772 (271)	No	With cast: Sensitivity Specificity AUC Accuracy Without cast: Sensitivity Specificity AUC Accuracy	 92% (90–94%) 88% (84–92%) 0.96 (0.94–0.97) 91% (89–93%) 86% (81–91%) 89% (84–93%) 0.94 (0.91–0.96) 88% (85–91%)	No	Yes, contact corresponding author
Blüthgen et al., 2020	Detection and localization	DL: ViDi Suite Version 2.0	PA and lateral	Two (fracture yes/no)	2 radiology residents	Trained: 524 (166) Tested: Internal: 100 (42) External: 200 (100)	Yes	**Detection** Internal dataset (model1; model2) Sensitivity Specificity AUC External dataset (model1; model2) Sensitivity Specificity: AUC: **Localization** Internal dataset: (AP,LAT,Combined views) Model 1 Model 2 External dataset: (AP,LAT,Combined views) Model 1 Model 2	 81% (58 – 95%); 90% (70 – 99%) 100% (88 – 100%); 97% (82 – 100%) 0.95 (0.85 - 0.99); 0.96 (0.87 - 1.00) 80% (66 – 90%); 82% (69 – 91%) 86% (73 – 94%); 78% (64 – 88%) 0.87 (0.79 - 0.93) 0.89 (0.81 - 0.94) 100%, 88%, 94% 94%, 87%, 89% 91%, 92%, 88% 100%, 89%, 93%	Yes	No
Cohen et al., 2022	Detection	CNN: Boneview	AP, oblique and specific views of the carpus	Two (fracture yes/no)	3 senior musculoskeletal radiologists	Trained: 1342 Validated: 192 Tested: 383 (166)	Yes	All wrist fractures Sensitivity Specificity Distal radius (166) sensitivity	 83% (78–87%) 96% (93–97%) 89%	Yes	No
Gan et al., 2019	Detection	CNN: inception-v4	AP	Two (fracture yes/no)	3 senior orthopedists	Trained: 2040 (1491) Tested: 300 (150)	No	Sensitivity Specificity AUC Accuracy Youden index	90% (85-95%) 96% (93-99%) 0.96 93% (90-96%) 0.86 (0.80-0.91)	Yes	No
Hardalac et al., 2022	Detection	CNN: WFD-C	N.A.	Two (fracture yes/no)	1 radiologist and 2 orthopedists.	Trained: 434 (all) Validated: 54 (all) Tested: 54 (all)	No	AP50	86.39	No	Yes, through Github

Table 2. Description of studies

Author, year	Study type	AI models used (type)	Projection of radiograph	Output classes	Ground truth label assignment	N of radiographs (n of fractures)	External validation	Performance metrics	Performance outcomes	Comparison CNN vs. radiologist	Open access
Joshi et al., 2022	Detection and Localization	CNN: mask R-CNN	N.A.	Two (fracture yes/no)	Multiple orthopaedic surgeons and radiologist.	Trained: 221 (all) Validated: 63 (all) Tested: 32 (all)	No	Fracture detection: AP50 AP75 Fracture segmentation: AP50 AP75	 92.278 79.003 77.445 52.156	No	No
Kim et al., 2021	Detection	CNN: DenseNet-161 and ResNet-152	AP and bilateral oblique	Two (fracture yes/no)	Radiological reports	Trained: 8994 (4551) Tested: 990 (300)	No	Densenet-161: Sensitivity Specificity AUC Accuracy ResNet-152 Sensitivity Specificity AUC Accuracy	 90.3% ±1.4 90.3% ±1.3 0.962 90.3% ±1.3 88.6% ±1.0 88.4% ±1.0 0.947 88.5% ±1.0	No	No
Kim et al, 2018	Detection	CNN: inception-v3	Lateral	Two (fracture yes/no)	1 radiology registrar	Trained: 1111 (695) Validated: 139 Tested: 139 Extra test set: 100	Yes	External dataset: Sensitivity Specificity AUC	 90% 88% 0.954	No	No
Lee et al., 2023	Detection	DL: DeepLab v3 and NasNet	AP, Lateral, Oblique	Two (fracture yes/no)	1 orthopedic surgeon, 1 musco skeletal radiologist	Trained: 3032 Tested: 758 External validation: (332)	No	Internal dataset: Sensitivity Specificity Accuracy AUC	 97.2% (95.6–99%) 83.2% (80.7–95.7%) 87.2% (85.2–89%) 0.903 (0.887–0.918)	Yes	No
Lindsey et al., 2018	Detection	CNN	PA and lateral	Two (fracture yes/no)	Multiple orthopedic surgeons.	Trained: 31490 (NA) Validated: 1400 Internal test: 3500 External test:1400	Yes	Internal test: AUC External test: AUC Clinician dataset: Sensitivity Specificity AUC	 0.967 (0.960-0.973) 0.975 (0.965-0.982) 93.9% (83.2-98.0) 94.5% (90.6-97.2) 0.990 (0.971-0.997)	Yes	No
Min et al., 2023	Localization and classificatio n	DL: YOLOv5	PA	Location fracture. Extra- vs intra-articular fracture	Location: medical student. Classification: 3 orthopedic registrars	Trained: 334 (292) Tested: 66 (57)	No	Localization: Average IoU Classification: AUC Accuracy Sensitivity Specificity F1-score	 0.816 ± 0.071 0.82 81% 83% 73% 0.86		
Oka et al., 2021	Detection	CNN: VGG16	AP and lateral	Two (fracture yes/no)	Clinical diagnosis orthopedic surgeons	Trained: 743 (569) Validated: 120 (80) Tested: 120 (80)	No	Sensitivity Specificity Accuracy AUC	98.6% ± 1.8 96.7% ± 3.5 98.0% ± 1.6 0.991 (0.984–0.999)		

Table 2. Description of studies

Author, year	Study type	AI models used (type)	Projection of radiograph	Output classes	Ground truth label assignment	N of radiographs (n of fractures)	External validation	Performance metrics	Performance outcomes	Comparison CNN vs. radiologist	Open access
Raisuddin et al., 2021	Detection	DL: DeepWrist, Gradcam	PA and lateral	Two (fracture yes/no)	2 radiologists independently	Trained: 3873 (953) Tested: Trivial cases: 414 Hard cases: 210	No	Trivial cases Sensitivity Specificity AUC F1-score Hard cases Sensitivity Specificity AUC: Balanced accuracy F1-score Combination trivial hard: AUC	 97% (94-100%) 87% (79-93%) 0.99 (0.98-0.99) 0.95 (0.92-0.97) 60% (40-80%) 92% (87-0.97%) 84% (72-93%) 0.76 (0.65-0.87) 0.63 (0.44-0.80) 0.97 (0.95-0.98)	Yes	No
Suzuki et al., 2022	Detection	CNN: EfficientNet B2 - EfficientNet B5	AP and lateral	Two (fracture yes/no)	2 orthopedic surgeons.	Trained: 1333 (722) Tested: 300 (150)	No	Sensitivity Specificity AUC Accuracy	98.7% (92.8-99.8%) 100% (95.1–100%) 0.993 (0.949-0.997) 99.3% (96.3-99.9%)	Yes	No
Thian et al., 2019	Detection	CNN: Inception-ResNet Faster R-CNN	AP and lateral	Two (fracture yes/no)	2 radiologists	Trained: 13153 (2130) Validated on: 1461(341) External test set: 1048	Yes	Per study (AP-LAT combined): Sensitivity Specificity AUC	 98.1% (95.6-99.4%) 72.9% (67.1-78.2%) 0.895 (0.870-0.920)	No	No
Tobler et al., 2021	Detection and classification	CNN: ResNet18	Frontal and lateral	Two (fracture yes/no)	2 musculoskeletal senior radiologists	Trained: 7997 (3656) Tested: Set A: 582 Set B: 326	Yes	Detection (set A; set B): AUC Accuracy Fragment displacement (set A; set B): AUC Accuracy Joint involvement (set A; set B): AUC Accuracy Multiple fractures (set A; set B): AUC Accuracy	 0.975 (0.957-0.992); 0.983 93.8% 0.589 (0.463-0.715); 0.916 59.7% 0.618 (0.516-0.720); 0.898 63.7% 0.842 (0.774-0.911); 0.905 78.2%	Yes	No
Ureten et al., 2022	Detection	CNN: Resnet-50, VGG-16, Googlenet	N.A.	Two (fracture yes/no)	1 orthopedic surgeon and 1 radiologist	Trained /validated: 410 (275) Tested: 135	No	VGG-16; ResNet-50; GoogLeNet Sensitivity Specificity Accuracy Precision	 96.8%; 94.9%; 90.6% 90.3%; 84.2%; 85.9% 93.3%; 88.9%; 88.1% 89.7%; 82.4%; 85.3%	No	No
Zhang et al., 2023	Detection	DL: Ensemble model	AP and lateral	Two (fracture yes/no)	1 orthopedist and 1 radiologist	Trained: 4579 (2268) Validated: 979 (486) Tested: 978 (486)	No	Accuracy Sensitivity Specificity	97.0% (95.71–97.96%) 95.7% (93.44–97.13%) 98.4% (96.73–99.18%)	No	

N.A.: Not assessed AI: Artificial intelligence. DSS: decision support systems. CNN: Convolutional Neural Networks. DL: deep learning. AUC: Area Under the Curve. AP50/AP75: Average precision 50/75. ResNet: Residual network. VGG: Visual geometry group. WFD-C: wrist fracture detection-combo. PA: Posterior-Anterior. AP: Anterior-Posterior. LAT: Lateral. ±: standard deviation. IoU: intersection over union (average overlap)

DISCUSSION

This systematic review provides an overview of various computer vision algorithms for detecting and classifying DRFs on plain radiographs. Overall, the included studies showed that the performance of DRF detection is excellent, with accuracies and AUC up to 100% and 0.99, respectively. Compared with clinicians' performance, AI had at least comparable and often better results. The development of a DRF classification model of DRF reported accuracies and AUC of 60-81% and 0.59-0.84, respectively. (29, 39) No studies describing algorithms predicting the loss of threshold alignment of DRFs were found.

This current study has several limitations. First, the comparability of the studies was limited. The studies were not consistent in the reported performance metrics. In addition, the studies used various types of DL and CNN models. However, the results of the studies show comparable performances of the different types of AI used, and the heterogenicity of the models did not affect our research questions. Secondly, the role of AI in the classification of DRF was only reported in two studies with different assessments of classifications. Therefore, evaluating AI's overall ability to classify DRFs is difficult. Thirdly, the ground truth was differently defined between studies or even not reported at all. Lastly, only six out of 18 studies performed an external validation of the AI model. To use AI in clinical practice, a model must be trained, tested, externally validated, and preferably prospectively validated. This validation is crucial to explore transportability and bias. (43) The lack of commonplace external validation shows that most algorithms cannot be used for daily practice yet.

The strengths of this review include the broad search in different databases and the quality assessment according to the modified MINORS criteria with AI-specific factors.

The included studies reported a sensitivity and specificity between 80-100% in detecting DRFs. There was a significant decrease in performance between the internal and external validation set on the separate assessment of the performance on AP and lateral views. This showed the necessity of training a DL model on data comparable to the intended target data. On the other hand, to eventually build a model capable of being used on an outside institution, further improving the AI model's performance

on external validation data sets is necessary. When AP and lateral views were combined, they showed similar performance on both internal and external sets. The reported AUC and accuracy were good to excellent across the included studies. The F1-score reported in the included studies showed poor to good precision.

Three studies used localization in addition to detection. This helps clinicians look into the black box of the algorithm, allowing them to check for any mistakes the algorithm might make. See Figure 2 for different options for presenting localizations. Future studies might choose to implement similar visualizations to help clinicians implement this in their daily practice.

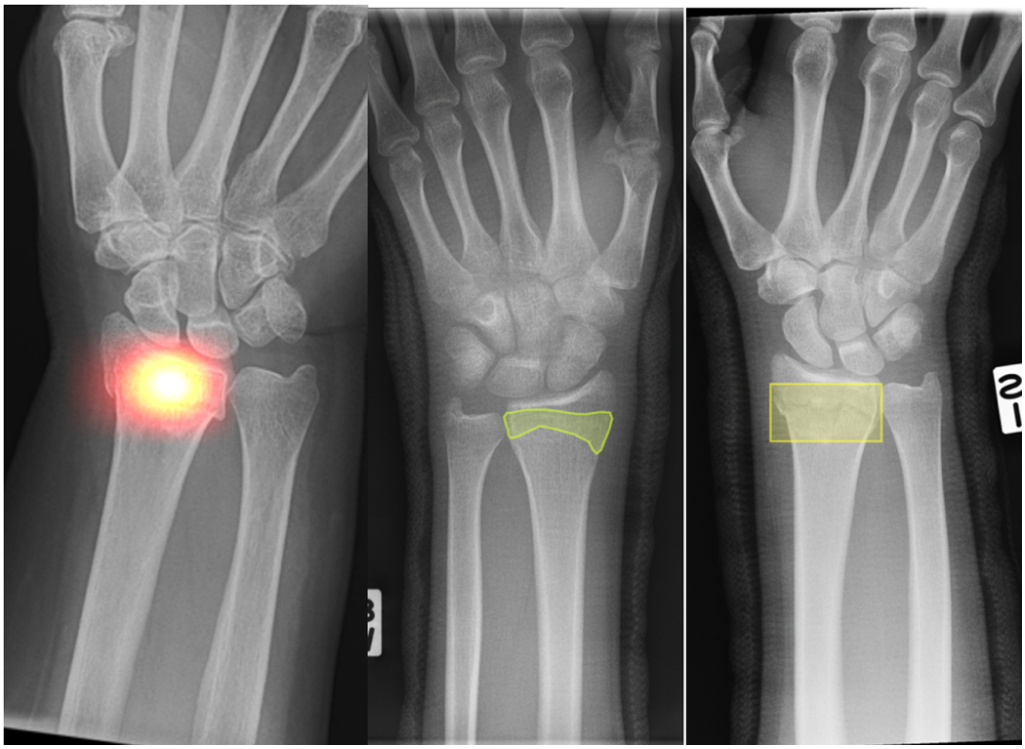

Figure 2. Different visualization of localization of fractures on PA radiographs. From left to right: a heatmap, a polygon and a bounding box.

Some of the included studies used the same CNN architecture backbone. For instance, Inception version 3 and version 4 were used in two studies (31, 33), both show comparable sensitivity, specificity, and AUC. In addition, one study (28) used a combined Inception- Resnet-Faster R-CNN and showed lower specificity and AUC.

The ResNet algorithm or backbone was used in five studies (21, 27-29, 35), all showing comparable performances of the algorithms.

In conclusion, AI models for detecting DRFs demonstrate promising performances across various metrics. However, results may vary depending on each study's dataset, model architecture, and evaluation methods. From a clinical perspective, DL and CNN algorithms have the potential to aid clinicians in medical imaging tasks and improve diagnostic accuracy in recognizing and consistently recording DRFs. Furthermore, we recommend focusing on diligent AI research, which involves presenting extensive outcomes, a comprehensive explanation of the dataset and the ground truth, and proper external validation.

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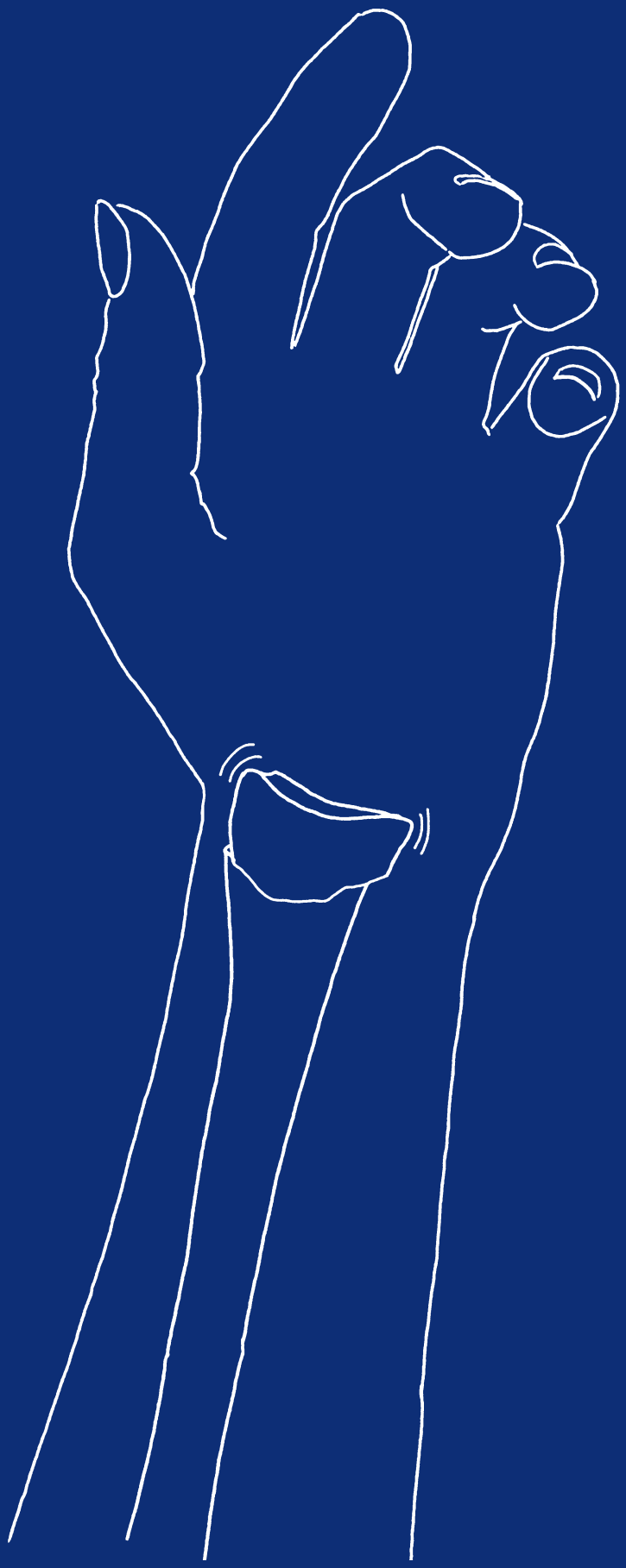

CHAPTER 4

Can surgeons accurately estimate loss of threshold alignment (instability) of a distal radius fracture after closed reduction and cast immobilization?

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ABSTRACT

Background

Estimation of the probability of loss of threshold alignment of distal radius fractures (DRFs) (often referred to as "fracture instability") after fracture reduction can help guide decisions about operative or nonoperative treatment. It is not clear whether such estimations are accurate or reliable.

We randomized surgeons to view post-reduction or pre-and post-reduction radiographs and asked: 1) Is there a difference in accuracy of estimation of loss of threshold fracture alignment (instability); 2) Are there any factors associated with the estimation of the probability of loss of threshold fracture alignment on the continuum; 3) Is there a difference in the interobserver agreement for predicting dichotomous loss of threshold fracture alignment?

Methods

In this survey-based experiment, 116 surgeons from several countries viewed radiographs of twenty displaced DRFs and estimated the probability of loss threshold alignment, both dichotomous (yes/no) and a continuous (0-100) scale. Half received only post-reduction radiographs and half received both pre- and post-reduction radiographs.

For dichotomous estimations we calculated accuracy, sensitivity, specificity, positive predictive value and negative predictive value, and Fleiss' Kappa (interobserver reliability). We used negative binomial regression analysis to identify factors associated with estimation of loss of threshold on a continuum.

Results

There was no difference in accuracy of prediction of loss of alignment between surgeons that viewed both pre- and post-reduction radiographs and those that only viewed post-reduction radiographs alone (accuracy of 55% (95% CI: 46%-62%) vs. 54% (95% CI: 51%-57%)). Greater probability of loss of threshold alignment on the continuum had modest associations with viewing pre-reduction radiographs and 11 to 20 years of experience. The interobserver agreement was fair in both groups:

0.26 (95% CI: 0.14-0.38) with pre-reduction radiographs and 0.28 (95% CI: 0.14-0.43) without.

Conclusion

The observation that estimations of loss of threshold DRF alignment (instability) have limited accuracy and reliability, even when viewing pre-reduction radiographs, reminds surgeons of the DRF treatment uncertainties and the importance of patient involvement.

INTRODUCTION

A notable percentage of displaced fractures of the distal radius (DRFs) treated with closed reduction and cast immobilization displace beyond threshold alignment during the first weeks of treatment (1, 2). Surgeons may be accustomed to the terms "fracture instability" and "fracture redisplacement" rather than loss of threshold alignment, but it's important to be explicit and unambiguous. The terms "instability" and "redisplacement" imply a threshold of radiographic deformity and judgment that the alignment of the fractured radius has surpassed that threshold. The degree of visible deformity, limitation of mobility of the wrist and forearm, and levels of discomfort and incapability can vary substantially for given threshold of displacement (3, 4). Framing a threshold as a boundary that decides when a person stands to benefit or not benefit from surgery can be misleading.

Nevertheless, many surgeons and organizations use thresholds as guidelines for treatment decisions. The Dutch guidelines--based on the AAOS guidelines--describe thresholds for alignment at which to consider an offer of operative treatment, considering additional measures such as volar angulation, ulnar ward inclination, and translation (10). Mindful of the limitations of thresholds of acceptable alignment, accurate and reliable estimations of the probability of loss of threshold fracture alignment might nevertheless be helpful to patients considering surgery. Prior studies found factors such as older age, and greater initial ulnar positive variance, volar tilt, and dorsal comminution to be associated with loss of threshold alignment after reduction and immobilization (5–7). The Edinburgh Wrist probability Calculator (EWC) was developed based on statistical analysis of thousands of displaced DRFs treated with closed reduction and splint or cast immobilization (7). There is limited evidence regarding the reliability and accuracy of these methods for estimating the probability of loss of threshold alignment after closed reduction (7–9). One study found that the estimations from the Edinburgh Wrist probability Calculator (EWC) had limited diagnostic performance (8). Another study found that ulnar variance, radial height, and radial inclination were associated with the LaFontaine criteria and the EWC, but not with final dorsal tilt or carpal malalignment (9).

When considering estimations of the probability of loss of threshold alignment, another consideration is that pre-reduction radiographs may have useful information about initial displacement and fragmentation. However, in some settings pre-reduction radiographs may not be available. For instance, if a person has the fracture initially reduced at the emergency department of another hospital and then presents to the outpatient clinic where the pre-reduction radiographs are not available. It will be useful to know if the availability of pre-reduction radiographs improves the reliability and accuracy of estimations of the probability of loss of threshold alignment.

In this survey-based experiment orthopaedic trauma surgeons were randomized to view radiographs of a DRF after reduction, or before and after reduction. We asked: 1) Is there a difference in diagnostic performance characteristics (accuracy, sensitivity, and specificity) of estimation of dichotomous loss of threshold fracture alignment (instability); and 2) Are there any factors associated with estimation of the probability loss of threshold fracture alignment on the continuum; and 3) Is there a difference in the interobserver agreement for predicting dichotomous loss of threshold fracture alignment.

METHODS

Study design and setting

In this survey-based experiment we used the online questionnaire tool Survey Monkey® (Palo Alto, CA, USA) to administer the survey. Subjects viewed radiographs of several displaced DRFs treated with closed reduction and were asked to predict whether each DRF would lose alignment beyond the thresholds presented in the Dutch guidelines or not (10).

Participants

Members of the Science of Variation Group (SOVG), a collaboration of international orthopaedic, trauma and plastic surgeons, mostly from the US and Europe, that studies variation in healthcare using online experiments, were asked to participate. Members do not receive financial compensation for participation.

After an initial email invitation, non-responders were sent two weekly reminders. A total of 116 surgeons completed the questionnaire, with 92% being men, 43% residing in the United States, and 36% residing in Europe (Table 1). This is a typical number of participants. Approximately 200 participants complete at least one survey a year.

Patients with distal radius fractures included in the study

Suitable fractures were retrospectively selected from a level-1 trauma centre by searching the Picture Archiving and Communications System (PACS). Consecutive patients were collected from January 2017 to June 2020, and were included based on the following criteria: 1) A fracture of the distal radius displaced beyond acceptable threshold on one of the measurements (i.e., dorsal angulation, ulnar ward inclination) according to the most recent Dutch guidelines after trauma (Table 2) (10), 2) Age 18 years or older, 3) Closed reduction within 24-hours after emergency room visit, 4) Fracture alignment after reduction within acceptable thresholds according to the guidelines, 5) Additional radiographic documentation for a minimum of 6 weeks after injury to determine whether the fracture lost threshold alignment or not. Patients were excluded based on the following criteria: 1) Operative treatment before losing

threshold alignment or before 6 weeks, 2) Previous DRF on ipsilateral side, 3) Missing postero-anterior [PA] and lateral radiographs within 6 weeks of injury,

Table 1. Demographics of surgeons.

Variables	**Value***
N	116
Male	92% (107)
Continent	
US	43% (50)
Europe	36% (42)
Other	21% (24)
Years of practice	
0 - 5	25% (29)
6 - 10	22% (25)
11 - 20	30% (35)
21 - 30	23% (27)
Supervising	82% (95)
Subspecialty	
Fracture surgeons	43% (50)
Hand/wrist	35% (41)
Shoulder/elbow	9% (11)
Other	12 % (14)
Group	
Pre- & Post-reduction Radiograph	48% (56)
Pre-op Radiograph	52% (60)

*Value is displayed as median with interquartile range for continuous non-parametric variables, as mean with standard deviation for continuous variables with normal distribution, and as number with percentage for categorial variables;

4) Radiographic obliquity judged sufficient to alter radiographic measurements. Patients were included by an independent researcher not involved in patient care and confirmed by two independent orthopaedic surgeons and senior authors.

A total of twenty fractures were selected, 11 did not lose threshold alignment during follow-up ("stable"), 9 did lose threshold alignment ("unstable") according to one of the measurements of the guideline. From these cases, PA and lateral views of radiographs obtained immediately after injury and radiographs after manipulative reduction and cast immobilization were collected.

Table 2. Threshold for acceptable alignment according to the Dutch guidelines. A fracture has lost threshold alignment if one of the following measurements has been reached.

< 10° of dorsal angulation of the articular surface on a lateral radiograph
< 20° of volar angulation of the articular surface on a lateral radiograph
< 15° of ulnar ward inclination of the articular surface on the PA view (often referred to as radial inclination)
< 3 mm of ulnar positive variance
< 2 mm intra-articular step-off
No significant translation and intact radiocarpal alignment on the lateral radiograph
No significant translation on the PA radiograph

Survey based online experiment

Each surgeon was randomized (simple randomization, 1:1) to receive either 1) post-reduction radiographs alone, or 2) pre- and post-reduction radiographs. All surgeons that participated reviewed the Dutch guidelines for acceptable alignment. For each of the fractures the age and sex of the patient at time of the trauma was presented. Participants were asked if the fracture would lose threshold alignment according to the guidelines (i.e., deemed unstable) as a binary yes or no. They were also asked to rate the probability the fracture would lose threshold alignment on a scale from 0-100, with 0 being not likely at all, and 100 being certain to lose threshold alignment.

Statistical analysis

Descriptive statistics was performed for all participants. Continuous variables were described using means and standard deviations, and categorical variables were described using absolute numbers with percentages.

Accuracy, sensitivity, specificity, positive predictive value (PPV) and negative predictive value (NPV) were reported to describe the ability of surgeons to predict loss of threshold alignment. Fleiss' kappa was used to assess the interobserver agreement of the surgeons in each group. The kappa scores were interpreted using the classification system by Landis and Koch (11). A mixed multilevel logistic regression analysis was used to calculate an odds ratio between both groups.

A negative binomial regression analysis was used to see if there are any factors associated with predicting loss of threshold on a scale from 0-100.

RESULTS

Post-reduction radiographs alone versus pre- and post-reduction radiographs

Overall accuracy to estimate distal radius fracture instability (loss of threshold alignment yes/no) was low: surgeons who only viewed post-reduction radiographs had a near similar accuracy of 55% (95% CI: 51%-57%), compared to surgeons who viewed both pre- and post-reduction radiographs who had an accuracy of 54% (95% CI: 46%-62%). Viewing only post-reduction radiographs was associated with significantly worse sensitivity of 44% (95% CI: 42%-47%) compared to 56% (95% CI: 53%-59%), and significantly better specificity of 45% (95% CI: 42%-48%) compared to 31% (95% CI: 28%-34%) compared to viewing both pre- and post-reduction radiographs. The PPV and NPV were not significantly different: 50% (95% CI: 47%-52%) compared to 49% (95% CI: 46%-52%) and 40% (95% CI: 37%-43%) compared to 37% (95% CI: 34%-40%) respectively (Table 3). The logistic regression model confirmed that additionally viewing pre-reduction radiographs was not associated with more accurate prediction of loss of threshold alignment (Table 4).

Table 3. Accuracy of predicting loss of threshold alignment.

Randomization group	Accuracy (%)*	Sensitivity (95% CI)	Specificity (95% CI)	Positive predictive value (95% CI)	Negative predictive value (95% CI)
Post-reduction Radiographs	55% (51% - 57%)	44% (42% - 47%)	45% (42% - 48%)	50% (47% - 52%)	40% (37% - 43%)
Pre- and Post-reduction Radiographs	54% (46% - 62%)	56% (53% - 59%)	31% (28% - 34%)	49% (46% - 52%)	37% (34% - 40%)

*Value is displayed as a percentage with total amount of correct predictions/total amount of predictions; CI = Confidence Interval

Table 4. Mixed multi-level logistic regression analysis of accuracy of predicting loss of threshold fracture alignment.

Randomization group	Odds Ratio (95% Confidence Interval)	Standard Error	*P*-value	Δ Akaike
				1.4
Post-reduction Radiograph	*Reference value*			
Pre- & Post-reduction Radiograph	0.81 (0.65 to 1.0)	0.091	0.063	

Estimated loss of threshold alignment on the continuum (probability of instability)

Greater probability of loss of threshold alignment on the continuum was associated with viewing pre-reduction radiographs and 11 to 20 years of experience (Table 5).

Interobserver agreement

Surgeons who viewed both pre- and post-reduction radiographs and surgeons who only view post-reduction radiographs had comparable interobserver agreements (Kappa of 0.28 (95% CI: 0.14-0.43) compared to 0.26 (95% CI: 0.14-0.38)), both considered fair (Table 6).

Table 6. Interobserver agreement

	Kappa	95% Confidence Interval	P-value
Pre- and post-reduction radiographs	0.28	0.14-0.43	**<0.01**
Post-reduction radiographs	0.26	0.14-0.38	**<0.01**

Bold indicates statistical significance, P < 0.05.

Table 5. Negative binominal regression analysis of surgeon factors associated with predicting loss of threshold alignment on a scale from 0-100

	Regression Coefficient (95% Confidence Interval)	**Standard Error**	***P*-value**	**Δ Akaike**
Randomization group				-3.4
Post-reduction Radiograph	*Reference value*			
Pre- & Post-reduction Radiograph	0.13 (0.079 to 0.18)	0.027	**<0.01**	
Gender				-1.9
Women	*Reference value*			
Men	0.060 (-0.037 to 0.16)	0.049	0.23	
Continent				-3.0
US	*Reference value*			
Europe	0.012 (-0.056 to 0.080)	0.035	0.72	
Other	-0.068 (-0.15 to 0.010)	0.040	0.09	
Years of practice				-6.7
0 to 5	*Reference value*			
6 to 10	-0.040 (-0.12 to 0.043)	0.042	0.35	
11 to 20	0.10 (0.023 to 0.18)	0.039	**0.01**	
21 to 30	0.069 (-0.0061 to 0.14)	0.038	0.07	
Supervising				-1.9
No	*Reference value*			
Yes	0.054 (-0.018 to 0.13)	0.037	0.14	
Subspecialty				-3.9
Hand/wrist	*Reference value*			
Shoulder/elbow	-0.032 (-0.13 to 0.069)	0.051	0.53	
Fracture surgeons	0.056 (-0.012 to 0.12)	0.036	0.11	
Other	-0.048 (-0.14 to 0.047)	0.049	0.32	

Bold indicates statistical significance, P < 0.05.

DISCUSSION

The choice between operative and nonoperative treatment can be based, in part, on estimations of the probability of loss of threshold alignment, sometimes referred to as 'distal radius fracture instability' (7–9). The accuracy and reliability of these estimations, and factors associated with more accurate estimations, are not completely understood (8, 9). We studied surgeons' estimation of loss of threshold fracture alignment and found that they have limited accuracy and reliability whether or not pre-reduction radiographs are available.

Limitations

This study has a number of limitations. First, this is a survey-based experiment, which is a partial representation of actual patient care. Surgeons were provided with radiographs, age and sex, but other aspects of health and activity were not available. However, previous research shows that these other aspects of health do not necessarily correlate with treatment recommendations19, and collecting other health aspects was not possible due to the retrospective nature of our data. Furthermore, some argue that the quality of the cast immobilization might also be associated with loss of threshold alignment, which is difficult to judge on radiographs. On the other hand, this also represents standard clinical practice, where supervising surgeons are not always present when the cast is being applied, and only see the post-reduction radiographs. Also, evidence to date suggests that immobilization type is not associated with loss of alignment (24, 25). Third, the radiographic parameters used in the Dutch guidelines are somewhat arbitrary and usage of other parameters might result in different predictions. However, the guidelines are evidence based, have recently been revised, and have similarities to other guidelines such as the AAOS guidelines (10). Finally, there is a risk in studying loss of threshold alignment that we may reinforce an emphasis on such determinations. What we elaborate to promote is by further elaborating the potential weak points of the use of thresholds is that the role of the specialist is not to decide for the patient. Rather to guide these patients to a decision consistent with what matters most to them, unclouded by common misconceptions and based on the most current evidence.

Post-reduction radiographs alone vs. pre- and post-reduction radiographs

The observation that additionally viewing pre-reduction radiographs was not associated with greater accuracy in dichotomous estimations of loss of threshold alignment suggests that either there is sufficient information on the post-reduction radiographs or that surgeons have limited accuracy in estimating the probability of loss of threshold alignment at all, no matter the amount of data provided. Tools such as the EWC use pre-reduction radiographs to estimate the probability of loss of threshold alignment. However, attempts to validate this tool suggest it may have limited accuracy (7–9). One interpretation of our findings is that post-reduction radiographs are sufficient and tracking down pre-reduction radiographs may not improve accuracy. This might mean that pre-reduction displacement of the fracture is not associated with post-reduction loss of threshold alignment, however, research to date indicates that there is correlation, so perhaps both pre- and post-reduction radiographs carry similar information (5–7), or the unreliability and variation in treatment strategies minimizes the influence of pre-reduction radiographs.

Estimated loss of threshold alignment on the continuum

The observation that higher estimated probability of loss of threshold alignment on a continuum was modestly associated with viewing pre-reduction radiographs suggests that pre-reduction images add concern, without improving accuracy on the dichotomous scale. This is consistent with evidence that exposure to more detail about fractures often increases the enthusiasm for surgery with relatively limited improvement in agreement between surgeons or accuracy with regards to a reference standard (12–15).

Interobserver agreement

The observation that whether or not surgeons reviewed pre-reduction radiographs interobserver agreement was fair, is consistent with a large body of evidence suggesting that large groups of surgeons working in disparate locations have varied interpretations of radiographs, probably due to varied attention to, and emphasis on,

certain factors (16). These variations in surgeon interpretation of radiographs might explain a part of the variation in treatment of DRFs: In Australia 80% of patients are offered surgery, while in most of Europe this is 15-30% (17, 18). It must also be considered that surgeon interpretations may be influenced by financial and other incentives. Furthermore, if surgeons do not agree with each other on which fractures are likely to lose threshold alignment, it's logical to conclude that a patient might receive different treatment recommendations based on the surgeon they consult. This is in line with previous research that shows that surgeons often do not agree with each other (i.e., poor inter-surgeon agreement) in both classifications of fractures and in recommendations for treatment of upper extremity disorders (19-23).

Conclusion

This survey-based experiment demonstrates limited accuracy and reliability in estimations of loss of threshold alignment of DRFs after closed reduction and cast immobilization, in previous studies often referred to as 'prediction of distal radius fracture instability'. In many parts of the world, the practice has long been to follow fracture alignment radiographically over time and selectively offer operative treatment if threshold alignment is lost (9). That strategy may offer several advantages compared to offering surgery based on potential for loss of threshold alignment, such as the prevention of surgery, including its potential complications, if there is no loss of threshold alignment. Future research can determine if it is possible to make reliable and accurate estimations of potential for loss of threshold alignment, perhaps using artificial intelligence, in particular the field of computer vision using imaging processing with deep learning or other machine learning (ML) techniques (26). An improved estimation of probability for loss of threshold alignment using a ML driven calculator, may facilitate shared decision making so that we can focus on patient values and preferences, rather than discussing uncertain probabilities of radiographic outcome.

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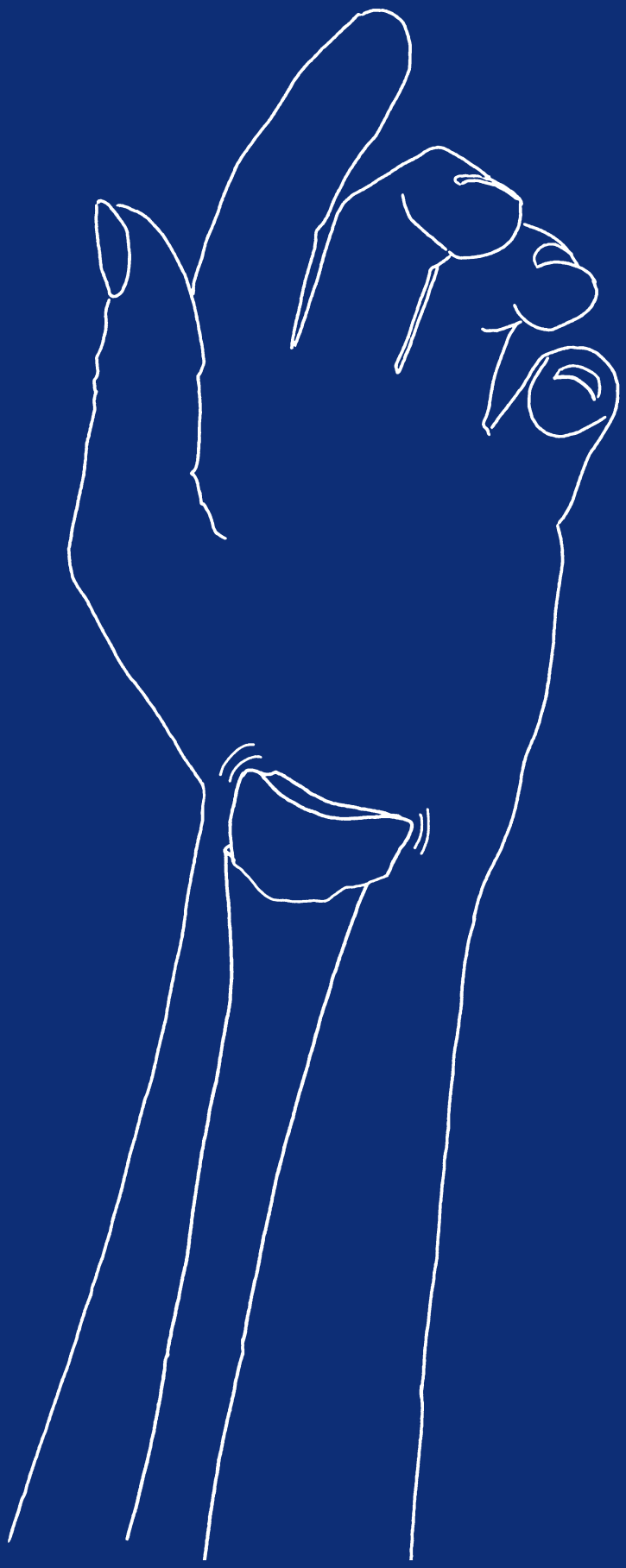

CHAPTER 5

The prediction of loss of threshold alignment of distal radius fractures: Does computed tomography increase accuracy and inter-observer agreement?

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ABSTRACT

Objectives

Estimates of the probability of loss of threshold alignment of a displaced fracture of the distal radius (DRF) after reduction and immobilization help patients and surgeons make treatment decisions. The greater detail of Computed tomography (CT) has the potential to improve the accuracy and reliability of such estimates. In a scenario-based, randomized experiment, factors associated with accuracy and reliability of estimates of loss of threshold alignment of displaced DRFs, including viewing CT and other patient and surgeon factors were investigated.

Methods

Members of The Science of Variation Group (n=115) viewed 15 sets of pre- and post-reduction radiographs of displaced DRFs. By random assignment, half also viewed post-reduction CT-scan. The accuracy of prediction of loss of threshold alignment for both groups was calculated, and the inter-observer agreement was assessed using Fleiss kappa. Factors associated with dichotomous and continuous estimation of loss of threshold alignment were sought in mixed multilevel logistic and linear regression analyses.

Results

Dichotomous estimation of loss of alignment on radiographs and CT-scans had limited accuracy (64% and 70% respectively) and was associated with patient (women and older age) and surgeon factors (women surgeons and surgeons in practice for 21 to 30 years). Higher probability of loss of alignment was associated with viewing CT imaging. Both estimations were relatively unreliable: radiographs alone kappa=0.33; CT-scans: kappa=0.27).

Conclusion

The observation that the accuracy and reliability of estimations of loss of threshold alignment are limited even when viewing CT images emphasizes the points to the possibility that it may not be possible to appreciably reduce uncertainty. Instead, we

advocate for a personalized approach to treatment decisions, considering patient and surgeon factors.

HIGHLIGHTS

- Estimates of the probability of loss of threshold alignment of a displaced fracture of the DRF help patients and surgeons make treatment decisions.
- The accuracy and reliability of estimations of loss of threshold alignment by surgeons are limited even when viewing CT images.
- Improved prediction tools in DRF alignment loss would be complementary within broader, patient-focused framework.

INTRODUCTION

Background

A displaced fracture of the distal radius (DRF) can lose threshold alignment after manipulative reduction and cast or splint immobilization (1-4). Loss of thresholds alignment includes increased of angulation, loss of inclination, positive ulnar variance, or the occurrence of an intra-articular step-off or gap. Factors associated with loss of threshold alignment in prior studies include age, gender, amount of dorsal or volar comminution, ulnar variance, and dorsal angulation (1, 3-7). MacKenney et al. (5) and Lafontaine et al (8) also suggested methods to prospectively predict radiographic outcome of a DRF using a formula or as a set of five criteria, respectively.

Rationale

Previous studies found that the Edinburgh equation and Lafontaine criteria correlate with final radiographic parameters (4, 5). Regarding probability estimates of loss of threshold reduction, one study noted poor diagnostic performance of the Edinburgh equation (9) whereas a separate study found good performance, better than surgeon opinion alone (10). CT imaging may depict deformity and fragmentation better than radiographs, which can increase the accuracy and reliability of estimates of loss of threshold alignment (11-18). One study that compared surgeons evaluating radiographs with or without additional CT-scans found that CT was associated with increased inter-observer agreement on treatment recommendations for DRF's with high therapeutic uncertainty; and in contrast decreased inter-observer agreement for DRF's associated with high therapeutic certainty (19). Less is known about the association of additional CT-scans with estimates of probability of loss of threshold alignment.

Therefore, the research questions in this scenario-based, randomized, experiment are: What patient and surgeon factors (including viewing CT imaging or not) are associated with variation in: 1) accuracy of predicting loss of threshold alignment; 2) inter-observer agreement; 3) dichotomous and 4) continuous estimation of the likelihood that a DRF will lose thresholds alignment.

METHODS

Study design

In an Institutional Review Board (IRB) approved, cross-sectional scenario-based study, members of the Science of Variation Group (SOVG) were invited to participate in this study in October 2022. Surgeons were blinded from the study design and hypothesis and randomized 1:1 to review pre- and post-reduction radiographs alone, or pre- and post-reduction radiographs with additional CT-scans.

Participants

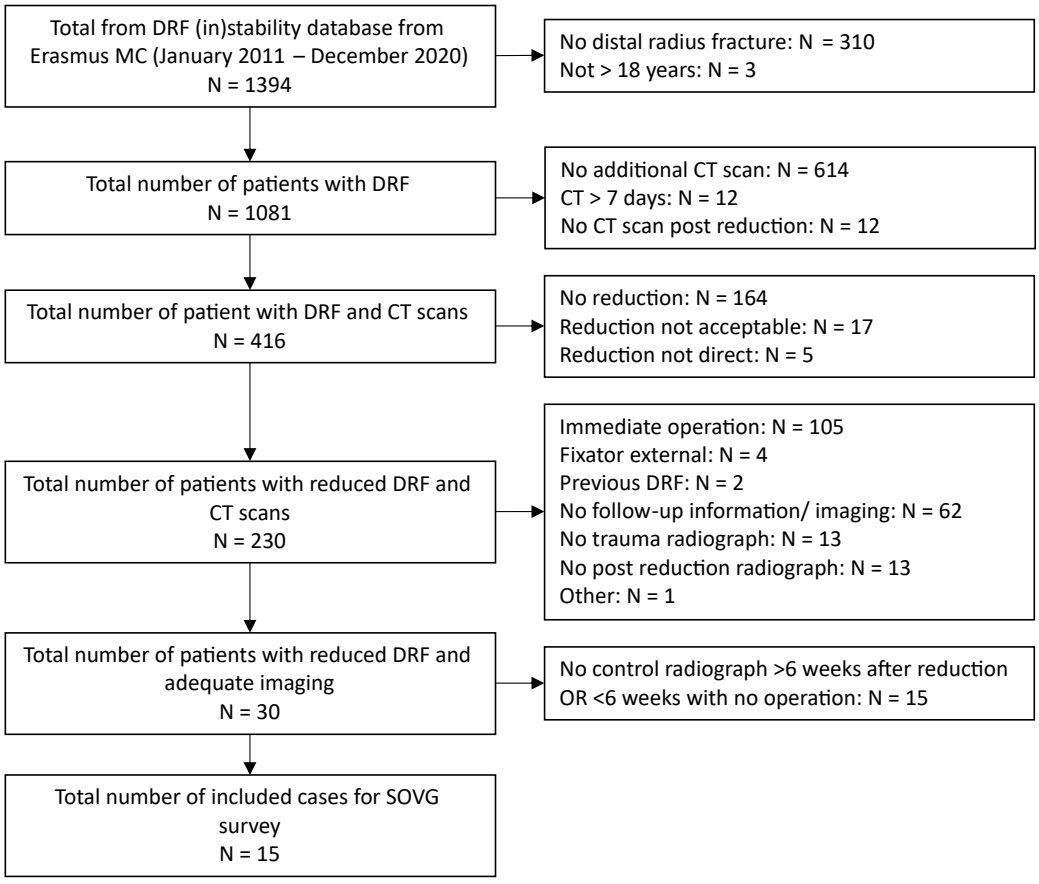
The SOVG is a collaborative that studies variation in healthcare. The generalizability of SOVG scenario-based experiments is determined by variation in ratings sufficient to allow measurement of statistical associations. The relationships identified in a scenario-based experiment are likely reproducible in other samples with sufficient variation, while the absolute rates observed are probably not reproducible in other samples. SOVG members are orthopaedic, plastic, and general trauma surgeons who treat fractures. Most members practice in the United States or Europe. While everyone is invited to join, and efforts to improve diversity have been made, most participating members are white men, practicing in an academic hospital. This – at least partly – reflects the current lack of diversity in our specialties and/or willingness to participate. Members receive group authorship or acknowledgement, but no financial compensation for their contribution.

Review case selection

A DRF database of an academic health center with DRFs treated between January 2011 and June 2020 was used. From this database the first 15 consecutive displaced and reduced DRFs that met inclusion and exclusion criteria were selected. The inclusion criteria were: 1) reduced distal radius fracture, 2) aged 18-years or older, 3) radiographs after injury and after reduction with additional CT-scan within 7 days, and 4) radiograph 6 or more weeks after reduction or having a radiograph deemed to have threshold malalignment before surgery. The database consisted of a total of 1081 DRFs. Of these patients, 230 had post-reduction CT-scans, for either better

visualization of the articular surface or pre-operation planning. Eventually, 200 cases were excluded according to the following criteria: a choice to operate based on alignment directly after reduction (109 fractures), no trauma-, post-reduction or follow-up radiographs (88 fractures), previous ipsilateral DRF (2 fractures), and one other. Of these 30 patients, fifteen had a radiograph at least 6 weeks after reduction or had a radiograph deemed to have threshold malalignment before surgery (Figure 1). Of the 15 fractures included, all fractures were dorsally displaced, 12 fractures involved the articular surface, and 3 of the articular fractures had a gap or step of more than 2 millimeters on the initial radiographs. Fracture alignment was measured to define whether the fracture was within thresholds for alignment according to the Dutch guidelines (20). Among the included fractures, nine eventually lost threshold alignment, of which three loss articular alignment. For the demographics of the included cases see Table 1.

Figure 1. Inclusion and exclusion flowchart



N: Number; DRF: Distal Radius Fracture; MC: Medical Center; CT: Computed Tomography; SOVG: Science Of Variation Group

Table 1. Demographics of cases

Variables	Value*
N	15
Women	60% (9)
Age at trauma onset (years)	52 [39-63]
Side of trauma	
Left	53% (8)
Right	47% (7)
Operation for DRF	
Yes	33% (5)
No	67% (10)
Time between control (weeks)	
Operated patients	12 (± 2.8)
Non operated patients	51 (± 5.2)

DRF: Distal radius fracture

*Value is displayed as median with interquartile range for continuous non-parametric variables, as mean with standard deviation for continuous variables with normal distribution, and as number with percentage for categorical variables;

Response variables

After pre- and post-reduction radiographs with or without additional CT imaging assessment, surgeons were asked to predict whether a fracture would lose threshold alignment (yes/no), and to rate the likelihood of a fracture losing threshold alignment on a scale from 0-100.

Explanatory variables

Explanatory surgeon variables were gender, continent where a surgeon practices, years of practice, supervision of surgical trainees, and subspecialty. There were 115 participants, 64 (56%) randomized to only see radiographs and 51 (44%) randomized to radiographs and CT-scans. One-hundred and three (90%) of the surgeons were men. The majority of the surgeons were from the US (48%) or Europe (34%), and most surgeons had an upper extremity specialization (49%) (Table 2). Explanatory patient variables were age, gender and fall mechanism.

Table 2. Demographics of surgeons.

Variables	Value*
N	115
Men	90% (103)
Continent	
US	48% (55)
Europe	35% (41)
Other	17% (19)
Years of practice	
0 - 5	23% (26)
6 - 10	19% (22)
11 - 20	33% (38)
21 - 30	25% (29)
Supervising	80% (92)
Subspecialty	
Fracture surgeons	37% (43)
Upper extremity surgeons	49% (56)
Other	15% (16)
Group	
Radiographs only	56% (64)
Radiographs & CT	44% (51)

US: United States; CT: Computed Tomography;
*Values are expressed as percentage with absolute numbers between parentheses;

Statistical analysis

A mixed multilevel logistic regression analysis was used to evaluate factors associated with dichotomous prediction of threshold loss of alignment accounting for nesting by surgeons, with alpha set at 0.05. An accuracy below 60% was considered poor, 60-70% moderate, 70-90% good and above 90% excellent (21). The accuracy was calculated by comparing the outcomes of the survey to the alignment on the follow-up radiographs, measured according to the Dutch guidelines (20).

A mixed multilevel linear regression analysis was used to seek patient and surgeon factors associated with surgeon rated likelihood of loss of threshold alignment.

The interobserver agreement was calculated using Fleiss' kappa. A kappa value of 0.01 to 0.20 represents slight agreement; 0.21 to 0.40 fair agreement; 0.41 to 0.60 moderate agreement; 0.61 to 0.80 substantial agreement, 0.81 to 0.99 almost perfect agreement and 1.00 defined perfect agreement. No agreement beyond chance alone is indicated by 0 and complete disagreement by -1.00 (22).

A mixed multilevel linear regression analysis was used to seek patient and surgeon factors associated with surgeon rated likelihood of loss of threshold alignment.

RESULTS

Accuracy of prediction of loss of threshold alignment

The accuracy of prediction of loss of fracture alignment after viewing only radiographs (64%; 95% CI = 0.61 to 0.67) was comparable to radiographs and CT (70%; 95% CI = 0.64 to 0.77) (Table 3). The odds of accurate prediction of loss of threshold alignment were similar when viewing CT or not (Odds Ratio [OR] = 1.1; 95% CI 0.91 to 1.4; *P* = 0.2) (Table 4).

Table 3. Accuracy of predicting loss of threshold alignment.

Randomization group	Accuracy (95% CI)*	Sensitivity (95% CI)	Specificity (95% CI)	Positive predictive value (95% CI)	Negative predictive value (95% CI)
Radiographs only	64% (0.61 to 0.67)	65% (62% to 68%)	51% (48% to 54%)	71% (68% to 74%)	45% (41% to 48%)
Radiographs & CT	70% (0.64 to 0.77)	68% (64% to 72%)	43% (39% to 47%)	74% (70% to 77%)	37% (33% to 41%)

*Value is displayed as a percentage with total amount of correct predictions/total amount of predictions; CI = Confidence Interval

Table 4. Mixed multilevel logistic regression analysis of accuracy of predicting loss of threshold alignment.

Randomization group	Odds Ratio (95% Confidence Interval)	Standard Error	P-value	Δ Akaike
				-5.9
Radiographs	Reference value			
Radiographs & CT	1.1 (0.91 to 1.4)	0.13	0.24	

Inter-observer agreement of prediction of loss of threshold alignment

The kappa score for inter-observer agreement of loss threshold alignment was comparable among surgeons viewing radiographs only (0.33; 95% CI = 0.16 to 0.50) and surgeons viewing both radiographs and additional CT imaging (0.27; 95% CI = 0.11 to 0.42).

Factors associated with variation in dichotomous prediction of loss of threshold alignment

Patient factors associated with surgeon prediction of loss of threshold alignment were woman patient gender (Regression Coefficient [RC] 0.75; 95% Confidence Interval [CI] = 0.52 to 0.98; *P* = <0.01), and older patient age (RC = 0.013; 95% CI 0.0066 to 0.019; *P* = <0.01). (Table 5) Surgeon factors associated with maintenance of alignment included women surgeons (male surgeons had a significant lower probability on average than female surgeons; RC = -0.77; 95% CI -1.2 to -0.32; *P* = <0.01) and surgeons with 21 to 30 years of experience (RC = 0.39; 95% CI 0.062 to 0.72; *P* = 0.020) and, but not assessing CT-scans. (Table 6)

Table 5. Mixed multilevel logistic regression analysis of patient factors associated with prediction of loss of threshold alignment Yes/No.

	Regression Coefficient (95% Confidence Interval)	**Standard Error**	**P-value**	**Δ Akaike**
Gender				26
Men	Reference value			
Women	0.75 (0.52 to 0.98)	0.12	**<0.01**	
Fall mechanism				27
Low energy trauma	Reference value			
High energy trauma	-0.22 (-0.49 to 0.046)	0.14	0.11	
Age	0.013 (0.0066 to 0.019)	0.0033	**<0.01**	29

Bold indicates statistical significance, P < 0.05.

Table 6. Logistic regression analysis of surgeon factors associated with prediction of loss of threshold alignment Yes/No.

	Regression Coefficient (95% Confidence Interval)	Standard Error	P-value	Δ Akaike
Gender				-2
Women	Reference value			
Men	-0.77 (-1.2 to -0.32)	0.23	**<0.01**	
Continent				5.9
US	Reference value			
Europe	0.17 (-0.098 to 0.44)	0.14	0.22	
Other	0.20 (-0.13 to 0.52)	0.17	0.23	
Years of practice				4.6
0 to 5	Reference value			
6 to 10	-0.011 (-0.37 to 0.34)	0.18	0.95	
11 to 20	-0.045 (-0.37 to 0.28)	0.16	0.78	
21 to 30	0.39 (0.062 to 0.72)	0.17	**0.02**	
Supervising				-1.5
No	Reference value			
Yes	-0.013 (-0.32 to 0.30)	0.16	0.94	
Subspecialty				4.4
Upper extremity	Reference value			
Fracture surgeon	-0.42 (-1.5 to 0.62)	0.52	0.43	
Other	-1.1 (-2.6 to 0.33)	0.74	0.13	
				0
Group				
Radiographs only	Reference value			
Radiographs & CT	0.15 (-0.087 to 0.39)	0.14	0.21	

Bold indicates statistical significance, P < 0.05.

Factors associated with continuous probability of loss of threshold alignment

Factors associated with higher probability a fracture will lose threshold alignment were female patient gender (RC = 9.8; 95% CI = 7.0 to 13; *P* = <0.01), older patient age (RC = 0.28; 95% CI = 0.20 to 0.37; *P* = <0.01; Table 7), surgeons with 21 to 30 years of practice (RC = 5.9; 95% CI = 1.6 to 10; *P* = <0.01), surgeons practicing in Europe (RC = 6.2; 95% CI = 2.7 to 9.8; *P* = <0.01) and viewing CT-scans (RC = 3.4; 95% CI 0.34 to 6.6; *P* = 0.029). The subspecialty other than upper extremity or fracture surgery (RC = -18; 95% CI = -35 to -0.57; *P* = 0.043) was associated with a lower probability (Table 8).

Table 7. Mixed multilevel linear regression analysis of patient factors associated with prediction of loss of threshold alignment on a scale from 0-100.

	Regression Coefficient (95% Confidence Interval)	**Standard Error**	**P-value**	**Δ Akaike**
Gender				38
Men	Reference value			
Women	9.8 (7.0 to 13)	1.4	**<0.01**	
Fall mechanism				-1.8
Low energy trauma	Reference value			
High energy trauma	-0.68 (-3.8 to 2.5)	1.6	0.67	
Age	0.28 (0.20 to 0.37)	6.6	**<0.01**	35

Bold indicates statistical significance, P < 0.05.

Table 8. Linear regression analysis of surgeon factors associated with prediction of loss of threshold alignment on a scale from 0-100.

	Regression Coefficient (95% Confidence Interval)	Standard Error	P-value	Δ Akaike
Gender				-14
Women	Reference value			
Men	-1.5 (-6.8 to 3.7)	2.7	0.57	
Continent				8.0
US	Reference value			
Europe	6.2 (2.7 to 9.8)	1.8	**<0.01**	
Other	2.9 (-1.3 to 7.0)	2.1	0.18	
Years of practice				5.0
0 to 5	Reference value			
6 to 10	-0.40 (-5.1 to 4.3)	2.4	0.87	
11 to 20	3.0 (-1.3 to 7.3)	2.2	0.17	
21 to 30	5.9 (1.6 to 10)	2.1	**<0.01**	
Supervising				-1.2
No	Reference value			
Yes	-1.9 (-6.0 to 2.3)	2.1	0.38	
Subspecialty				4.4
Upper extremity	Reference value			
Fracture surgeon	-3.7 (-17 to 9.3)	6.6	0.57	
Other	-18 (-35 to -0.57)	8.7	**0.04**	
				3.3
Group				
Radiographs only	Reference value			
Radiographs & CT	3.4 (0.34 to 6.6)	1.6	**0.03**	

Bold indicates statistical significance, $P < 0.05$.

DISCUSSION

To help patients make decisions regarding treatment options, it would be helpful to be able predict the probability of loss of alignment after reduction and splint or cast immobilization. CT might improve the accuracy and reliability of prediction of loss of threshold alignment since angle and distance measurement are more precise and it may depict fragmentation better than radiographs. This scenario-based experiment found that CT imaging did not improve the limited accuracy and fair reliability of prediction of loss of threshold alignment as compared to plain radiographs.

Limitations

This study has limitations. Firstly, the fractures were included by a single observer which can introduce observer bias. However, the fractures were included based on their radiographic reports written by a specialist, thus it was unlikely that this bias had effect on the results. Secondly, both radiographs and CT-scans in a DICOM format were transferred from the electronic medical record to a digital research environment and then incorporated in the survey as a MPEG4 video, which may have resulted in a reduced image resolution. However, a previous study on the evaluation of tibial plateau fractures on online CT-scans showed that the observer participation and interobserver reliability for the characterization of the fractures was better with MPEG4 than with DICOM videos (23). The method of image presentation will presumably not influence the results. Third, because the surgeons can have compared the fifteen cases throughout the survey to give a better prediction of loss of alignment, there was a possibility of learning bias. However, experienced surgeons were included in the study, and they received the cases in different and random order, so it is unlikely that this influenced the results. Furthermore, patients were excluded when they had immediate operation. However, in this study we did include cases if they had a radiograph deemed to have threshold malalignment before surgery, ensuring a representative sample of the clinic. Lastly, the majority of participants of the SOVG work in academic settings (80% supervise trainees), which may affect their values, training, and practice compared to the broader surgical community, limiting the generalizability of the study's findings.

Accuracy of prediction of loss of threshold alignment

The observation that the moderate accuracy of dichotomous estimation of loss of threshold alignment was not improved by CT suggests that routine use of CT will add potential for harm (both financial and iatrogenic) without providing benefit. These findings also raise the possibility that it may not be possible to reduce uncertainty regarding alignment after healing. In line with our findings, one prior study reported a moderate accuracy of prediction of alignment loss on only radiographs (10). However, in this study 18 observers assessed whether DRFs will heal above or below the malalignment threshold, while in our study 115 surgeons responded. One study reported a poor diagnostic performance of a different method, the Edinburgh equation (9). To our knowledge, the influence of additional CT imaging on the prediction of loss of threshold alignment was not previously assessed.

Inter-observer agreement of prediction of loss of threshold alignment

The observation that CT-scans did not improve the limited reliability of estimating the dichotomous probability of loss threshold alignment, contrasts with one previous study that found CT-scan was associated with greater inter-observer agreement on treatment planning of fractures with high therapeutic uncertainty (19).

Factors associated with dichotomous estimation of threshold alignment

The observation that viewing a CT was not associated with dichotomous estimation of loss of threshold alignment suggests that greater detail about the fracture is not a key contributor to these estimations. The observation that older patient age and woman patient gender were associated with dichotomous estimation of loss of threshold alignment is consistent with prior evidence that women and age are related to potential for loss of alignment, perhaps through greater a higher incidence of osteoporosis (1, 6, 24). The association with surgeon demographics is more difficult to interpret given that the subsets are relatively small and not necessarily representative of the average surgeons in that category.

Factors associated with continuous estimation of threshold alignment

The observation that continuous estimation of loss of threshold alignment was associated with the same factors as dichotomous estimation, but also with viewing CT imaging might indicate small differences in estimation associated with viewing CTs that can only be detected on the continuum. Notably, our results point to potential downsides of advanced imaging as CT may motivate surgeons to offer surgery without any tangible benefit (25).

Conclusion

The finding that CT imaging had limited association with estimation of the probability of loss of threshold DRF alignment and did not improve reliability argues against its routine use. When considering surgery on the basis of uncertain potential fracture displacement, people can weigh the potential for deformity against the risks, discomforts, and inconveniences of surgery, keeping in mind that later surgery can address deformity. Recognizing the multifaceted nature of fracture management, we highlight the importance of patient preferences, perceived invasiveness, complications, and expectations in the decision-making process. While improving the prediction in DRF alignment loss is valuable, it should be viewed as a complementary tool within a broader patient-centric context. Our findings encourage a shift to a more individualized and effective treatment strategies, fostering a balance between clinical evidence and patient-centered care.

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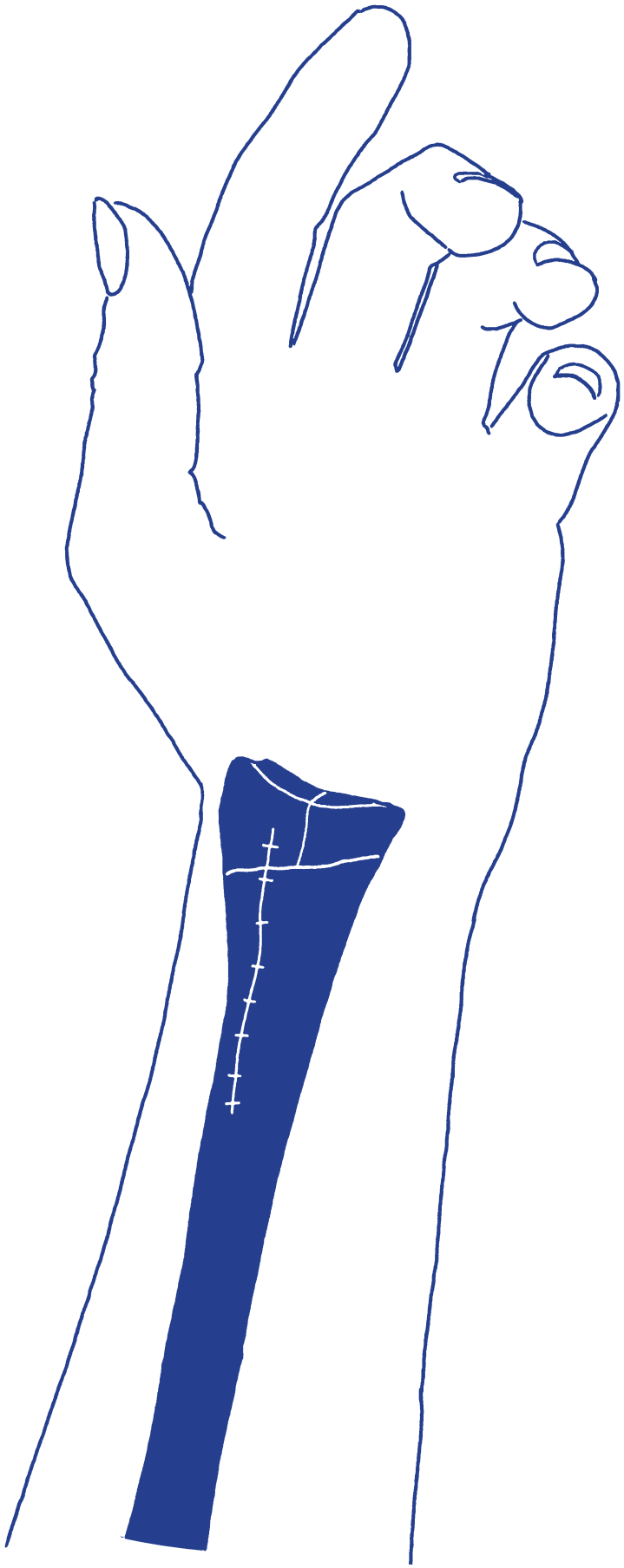
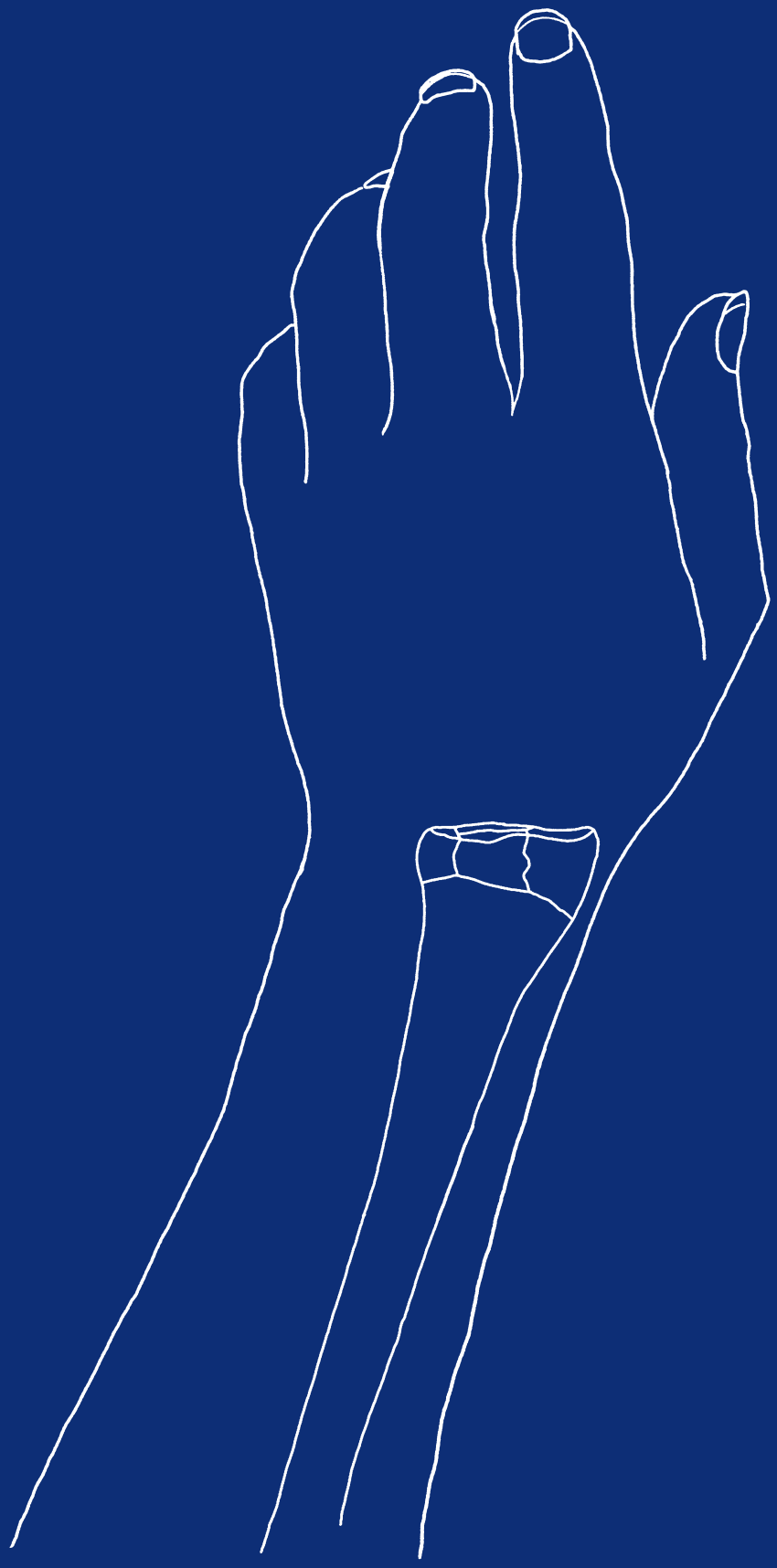


PART II

Treatment and complications of distal radius fractures



CHAPTER 6

Volar plate scaffold fixation of multi-fragmented intra-articular distal radius fractures: Fixation of the dorsal-ulnar corner

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ABSTRACT

Objectives

Volar locking plates (VLPs) are commonly used to treat displaced intra-articular distal radius fractures (DRFs), but multi-fragmented fractures may require additional dorsal fixation. This study assessed the outcomes of a technique combining VLP and a dorsal bone clamp, described here as "scaffold fixation", and evaluated whether dorsal ulnar corner (DUC) fixation is essential for radiocarpal alignment.

Methods

In this retrospective cross-sectional study of the ICUC® database, 87 patients with DRF with preoperative CT-identified DUC fragments were included. The range of motion was measured, and radiocarpal alignment was evaluated on postoperative and final follow-up radiographs. In addition, we compared cases with long screw purchases or short screw purchases in the DUC with respect to DUC size.

Results

No significant differences were found in flexion, extension, supination or pronation. DUC size was not associated with screw purchase nor with ROM outcomes. Radiocarpal malalignment was seen in 2% of patients postoperatively and 7% at final follow-up, with no difference between screw purchase groups.

Conclusion

Scaffold fixation with a VLP, aided by reduction using a dorsal bone clamp, effectively restores ROM and generally preserves radiocarpal alignment in DRF fixation, regardless of DUC screw purchase or DUC size in this cohort.

INTRODUCTION

Surgical fixation of comminuted intra-articular distal radius fractures (DRFs) can be challenging (1, 2). Volar locking plates (VLPs) have gained popularity for their ability to provide stable and effective fixation for most DRFs (3, 4). However, several studies have suggested that displaced multi-fragmented intra-articular DRFs cannot be stabilized effectively by volar plating alone and may require additional dorsal and or radial approaches to reduce and capture small but critical articular fragments (5-9).

The most challenging fracture fragments to address in AO/OTA C-type fractures are small fragments of the radial styloid, volar ulnar corner, or dorsal ulnar corner (10, 11). While much has been written about volar ulnar corner escape and the involvement of the radial styloid in radiocarpal fracture dislocation, less has been described regarding the dorsal ulnar corner (DUC) fragment and the ability of a VLP to stabilize it (12-15). The DUC fragment plays a crucial role in maintaining radiocarpal alignment and the stability of the distal radioulnar joint (DRUJ) (11, 16).

To address these challenges, fragment-specific plates or augments to existing VLP have been developed (7, 17-19). When only using a VLP, a recent study recommended utilizing longer screws greater than 75% of the volar-radial distal radius width to better capture and stabilize the dorsal ulnar corner fragment (16). However, screw prominence has its risks, including extensor tendinitis and extensor tendon rupture, leading most surgeons to avoid placing screws with any dorsal cortical penetration (20, 21). In addition, one challenge in the existing literature is that most of the recommendations are based on biomechanical studies or small case series of failure since postoperative computed tomography (CT) scans to assess screw depth, fragment size, and fragment fixation are uncommon. Using pre- and postoperative CT scans, our group previously demonstrated that dorsal ulnar corner fractures can often be effectively stabilized with a VLP and bone reduction clamp, creating a so-called "scaffold fixation" construct that relies on subchondral support and interfragmentary compression rather than direct fragment capture (22). In this context, scaffold fixation refers to the use of a volar locking plate as a stable volar buttress, combined with controlled reduction of dorsal fragments using a dorsal bone clamp, allowing the locking screws to support the reduced articular fragments indirectly through a

subchondral 'scaffold' effect. However, that study did not assess the impact of screw length on maintaining reduction or patient outcomes.

Analogous to the construction industry, the VLP functions as a "base plate", while reduction with a dorsal bone clamp allows placement of locking screws close to, but not penetrating, the dorsal ulnar cortex. These screws provide indirect subchondral support, collectively functioning as a scaffold that maintains reduction of the intra-articular fragments (See figure 1). This biomechanical concept differs from fragment-specific fixation in that stability is achieved through indirect support of the reduced fragments rather than direct fixation of the dorsal-ulnar corner fragment itself. The concept of the dorsal bone clamp for the fixation of DRFs with VLP is further explained in this video: https://www.vumedi.com/video/the-ball-tipped-fracture-reduction-forceps-an-integral-part-of-the-operative-treatment-of-distal-rad/.

Along with this, in this study we focused on the dorsal ulnar corner to determine if fixation into the dorsal ulnar corner fragment is always necessary to maintain radiocarpal alignment when using a VLP to stabilize comminuted intra-articular DRF, and we also assessed the surgical results. We hypothesized that "scaffold fixation" using short screws would not be able to stabilize the dorsal ulnar corner fragment in comminuted C-type fractures.

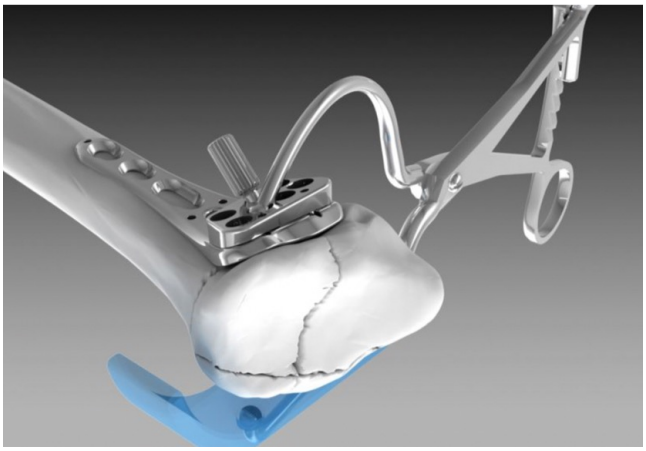


Figure 1. Radiolucent bone clamp, applied through the dorsal skin for fracture retention making use of the VA locking plate (Synthes) as a reduction template.

METHODS

Study design

We conducted this retrospective cross-sectional study within the open-access ICUC® database, assessing surgical outcome for range of motion (ROM), radiographic radiocarpal alignment and reported DRUJ instability following treatment of comminuted intra-articular DRF fixation with a VLP and a dorsal bone clamp. This study was Institutional Review Board-exempt as it used publicly available anonymous data.

Data set

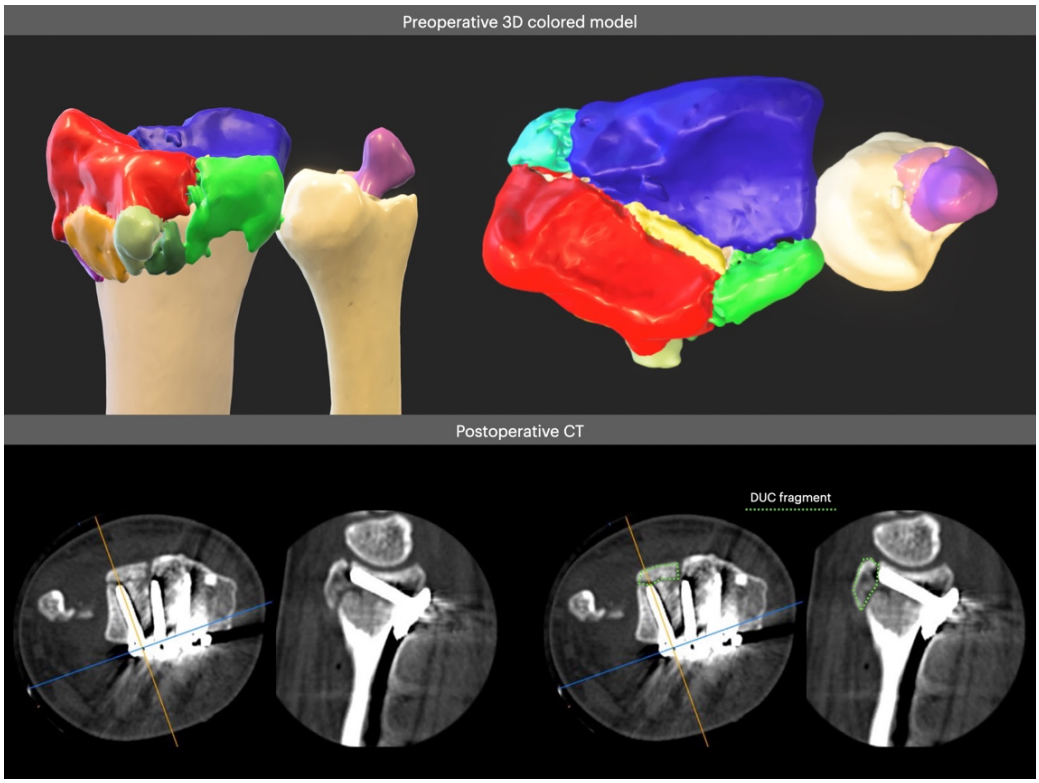
The ICUC® database utilized in this research represents a global collaborative initiative dedicated to the open-access dissemination of data on orthopaedic surgical procedures (23). The ICUC® Database is an anonymized, continuous series of cases recorded at five centres: Freiburg, Luzern, Milano, Montevideo, and Zurich. Continuous and complete registration of each relevant surgical step is collected. This information is kept anonymous and unchanged. For data to be included in the ICUC® database, access to follow-up data and informed consent for anonymous public use of the images is mandatory. The database includes for every case: all applicable radiographical imaging (pre-and post-reduction, post-operation, at follow-up), CT scans (post-reduction and post-operation), 3D-colored models, intra-operative radiographic imaging and photos), and clinical pictures of range of motion. All surgeons in the ICUC® database are hand-fellowship-trained senior surgeons, defined as highly experienced specialists or experts (24).

Patient variables and outcomes

We identified all intra-articular comminuted DRF within the database treated with a VLP up to June 2024. We included patients with a dorsal ulnar column fragment on a preoperative CT scan. The presence of the dorsal ulnar corner fragment was assessed by two researchers looking at preoperative interactive 3D-colored models and immediate post-op CT for each case (See the example in Figure 2). Exclusion criteria were multiple plate fixation or age < 18 years. The following baseline characteristics

were collected: age at the time of injury (years), sex (female/male), time to last follow-up radiograph and time of final ROM follow-up. All fractures were treated using a volar angular stable two-column distal radius plate (VA-LCP 2.4, DePuy Synthes, Switzerland).

Figure 2. Preoperative 3D-colored model and postoperative CT to assess dorsal ulnar corner. ICUC® ID-654.



Injury-specific variables included the degree of comminution with the total number of fragments and the occurrence of concomitant fractures. We classified the DUC fragment size according to feasibility for independent fixation on post-operation CT scanning. Specifically, fragments were categorized as (1) 'large' enough for independent fixation, (2) too 'small' for independent fixation, or (3) comminuted. Two senior authors independently reviewed the radiographic and 3D reconstruction images and assigned each fragment to one of these three categories. Discrepancies were resolved by consensus. Fixation was also categorized using a binary "long/short" screw purchase variable. Long screw purchase was defined as a screw

up to or through the cortex, and short screw purchase was defined as when screws did not reach the dorsal cortex (16, 18).

The primary outcome included the assessment of the ROM of the affected wrist as assessed through clinical images. ROM assessment was conducted using standardized digital photographs from the ICUC® database. Flexion, extension, supination, and pronation were consistently measured by a single researcher (LD) using a digital protractor on these digital photographs to ensure uniformity and minimize interobserver variability. This method provided a standardized approach to evaluating ROM across all patients. The minimal clinical ROM follow-up was three months post-surgery. In the cases that had hardware removal (n=7), the last ROM photo before removal was measured. The occurrence of clinically assessed DRUJ instability was described when reported in the patient reports.

The secondary outcome was the achievement of normal radiographic radiocarpal alignment, defined as the alignment of the volar axis of the radius to the capitate head (25, 26), as assessed on immediate postoperative radiographs and at final follow-up radiographs, assessed by two independent assessors. The minimal radiological follow-up was four weeks. The method used to determine the radiocarpal alignment is shown in Figure 3.

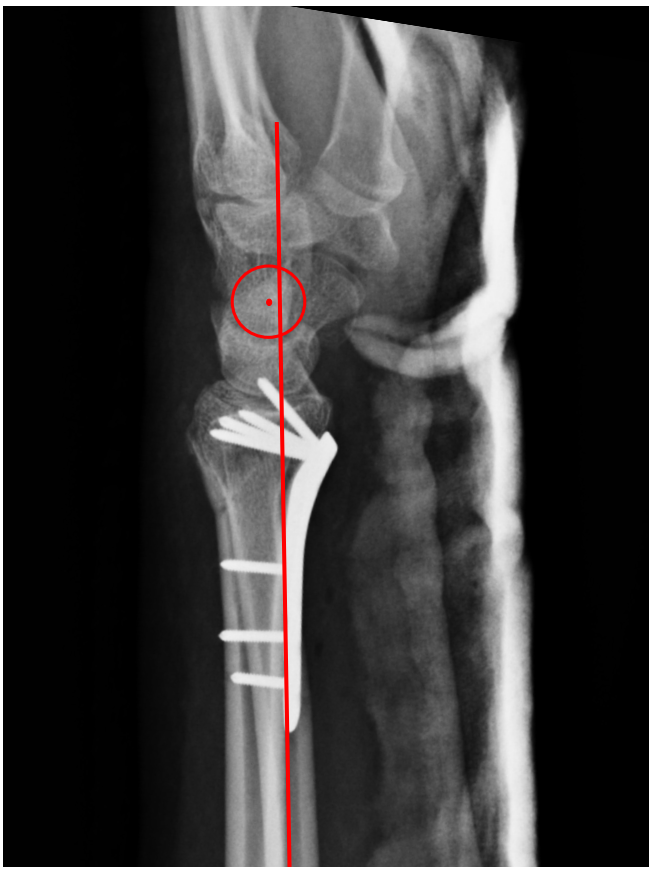


Figure 3. Radiocarpal alignment is defined as normal/ acceptable when a line drawn from the volar aspect of the distal radius intersects with the capitate head on a lateral radiograph of the wrist (see red line).

Statistical analysis

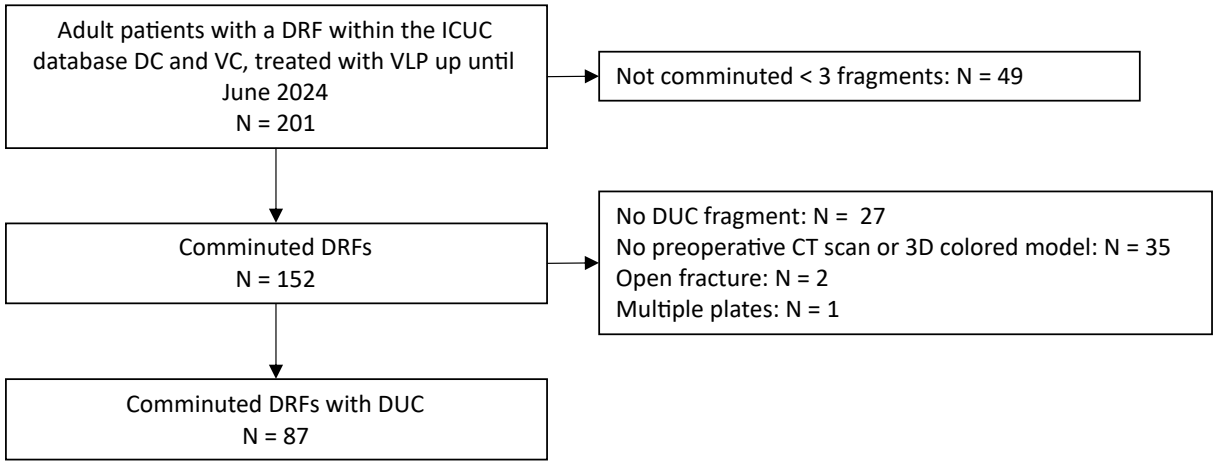
Descriptive statistics were used to summarize patient characteristics, changes in radiocarpal alignment and final ROM. Data distribution was assessed using the Shapiro-Wilk test. Missing data were not imputed. Continuous data are reported as mean with standard deviation (SD) for normal distributions or median with interquartile range (IQR) for non-normal distributions. Categorical data are presented as counts with percentages. A 2-sided Fisher exact test was used to analyze categorical variables, and an unpaired t-test/One-way ANOVA or a Wilcoxon rank sum / Kurskal-Wallis Rank Sum test for continuous variables. To assess the association between screw length and fragment size, a logistic regression analysis was performed. A p-value <0.05 was set to determine statistical significance.

RESULTS

Demographics of cases

Out of the 123 comminuted DRFs in the ICUC® database, we identified 87 DRFs with a dorsal ulnar corner fragment treated with a VLP. A flowchart of the inclusion process is shown in Figure 4. Baseline characteristics are demonstrated in Table 1. Of the included cases, the majority (77%) had four or more fragments. There was a concomitant ulnar styloid fracture in 41 (47%) cases. Short screw purchase was observed in 67 (78%) of the cases. Using small DUC fragments as the reference category, logistic regression showed no association between fragment size and screw purchase length (Table 2).

Figure 4. Inclusion and exclusion flowchart.



Range of motion

Ten cases were excluded from analysis due to ROM ≤ 3 months post-surgery, and in one patient, there were no ROM photos available. The median time to final follow-up on ROM was 52.5 weeks (IQR = 26.8-82.3). There was no significant difference between the final ROM in the cases with long screw purchase or short screw purchase concerning flexion, extension, supination and pronation (Table 3). Furthermore, there was no significant difference between final ROM and cases with a small, large or comminuted DUC fragment (Table 4).

Compared to a contralateral uninjured wrist, flexion, extension, supination, and pronation percentages did not significantly differ between groups (Table 3).

Furthermore, there was no significant difference between final ROM compared to a contralateral uninjured wrist and cases with a small, large or comminuted DUC fragment (Table 4).

Table 1. Descriptive statistics of patients and fracture characteristics

		Screw purchase in DUC		
Variables	**All patients**	**Long**	**Short**	**P-value**
N	87	19 (22%)	68 (78%)	
Age at trauma onset, Years (IQR)	60 [47.5-70]	65 [60-80]	55 [45-70]	**0.01***
Female, No. (%)	60 (69%)	17 (89%)	43 (63%)	**0.05****
Follow-up radiograph, Weeks (IQR)	54 [28.5-89]	47 [17.8-87.5]	54.5 [34-89]	0.38*
Follow-up ROM, Weeks (IQR)	46 [26-79]	33 [15.5-77.5]	48 [27.5-80]	0.35*
No. of total fragments (IQR)	4 [4-5]	4 [4-4]	4 [4-5]	**0.09****
Concomitant fractures	41 (47%)	8 (42%)	33 (48%)	0.48*
Number of fragments				**0.02****
3	20 (23%)	4 (21%)	16 (24%)	
4	37 (43%)	13 (68%)	24 (35%)	
≥5	30 (34%)	2 (11%)	28 (41%)	
Size of DUC fragment				0.62**
Small	51(59%)	10 (53%)	41 (60%)	
Large	28 (32%)	8 (42%)	20 (30%)	
Comminuted	8 (9)	1 (5%)	7 (10%)	
Post-reduction radiocarpal alignment, No. (%)				0.39**
Correct	85 (98%)	18 (95%)	67 (99%)	
Incorrect	2 (2%)	1 (5%)	1 (1%)	
Radiocarpal alignment at final follow-up, No. (%)				0.15**
Correct	81 (93%)	16 (84%)	64 (84%)	
Incorrect	6 (7%)	2 (11%)	4 (6%)	

Value is displayed as median with interquartile range for continuous non-parametric variables, as mean with standard deviation for continuous variables with normal distribution, and as number with percentage for categorical variables; *Wilcoxon Rank Sum test was done; **Fishers-exact test was done. **Bolt** indicated significance.

Table 2. Logistic regression analysis of DUC fragment size associated short screw purchase

DUC fragment size	OR	95% CI	P-value
Intercept (Small)	4.10	2.14 – 8.66	**<0.01**
Large	0.61	0.21 – 1.82	0.37
Comminuted	1.17	0.26 – 33.81	0.64

OR: Odds Ratio. Values in parentheses represent 95% Confidence Intervals.

Table 3. Final range of motion after VLP fixation, assessed for long and short screw purchase

	Screw purchase in DUC			
	All patients N = 76*	**Long N = 14**	**Short N = 62**	**P-value**
Flexion degree (SD)	70.9 (9.7)	69.3 (6.9)	71.3 (10.3)	0.49†
Flexion percent of contralateral (SD)	0.90 (0.12)	0.88 (0.11)	0.91 (0.13)	0.47†
Extension degree (SD)	78.4 (7.5)	75.4 (5.4)	79.1 (7.7)	0.06†
Extension percent of contralateral (SD)	0.93 (0.08)	0.91 (0.07)	0.94 (0.08)	0.19†
Supination degree [IQR]	88.5 [83.7-90.2]	88.7 [85.9-90.0]	88.5 [83.2-90.2]	0.87‡
Supination percent of contralateral (SD)	0.99 [0.95-1.00]	1.00 [0.98-1.02]	0.98 [0.94-1.00]	0.13‡
Pronation degree [IQR]	89.3 [85.1-90.6]	90.2 [87.9-92.0]	89.2 [85.1-90.5]	0.27‡
Pronation percent of contralateral (SD)	1.00 [0.97-1.02]	1.00 [0.97-1.02]	0.99 [0.96-1.02]	0.94‡

Value is displayed as mean with standard deviation for continuous variables with normal distribution and as median with interquartile range for continuous non-parametric variables, as mean with standard deviation for continuous variables with normal distribution, and as number with percentage for categorical variables; † Unpaired t-test was done; ‡Wilcoxon Rank Sum test was done. **Bolt** indicated significance. n=11 were excluded from analysis due to ROM not assessed, or ≤ 3 months post-surgery. *Additional n=3 were excluded from ROM percent of contralateral due to bilateral wrist fractures.

Table 4. Final range of motion after VLP fixation, assessed DUC fragment size

	DUC fragment size				
	All patients N = 76*	**Small N = 44**	**Large N = 21**	**Comminuted N = 8**	**P-value**
Flexion degree (SD)	70.9 (9.7)	71.9 (10.9)	69.6 (6.8)	69.7 (9.6)	0.61†
Flexion percent of contralateral (SD)	0.90 (0.12)	0.91 (0.14)	0.88 (0.12)	0.88 (0.09)	0.57†
Extension degree (SD)	78.4 (7.5)	79.7 (7.9)	76.5 (6.1)	76.4 (7.7)	0.19†
Extension percent of contralateral (SD)	0.93 (0.08)	0.94 (0.08)	0.93 (0.06)	0.92 (0.07)	0.59†
Supination degree [IQR]	88.5 [83.7-90.2]	88.9 [84.0-90.4]	88.5 [86.3-90.2]	84.3 [82.0-87.4]	0.20‡
Supination percent of contralateral (SD)	0.99 [0.95-1.00]	0.99 [0.96-1.01]	0.99 [0.97-1.02]	0.95 [0.93-0.99]	0.46‡
Pronation degree [IQR]	89.3 [85.1-90.6]	89.4 [85.0-90.8]	89.2 [86.9-90.5]	87.0 [74.2-90.9]	0.65‡
Pronation percent of contralateral (SD)	1.00 [0.97-1.02]	1.01 [0.98-1.02]	0.99 [0.96-1.01]	0.96 [0.92-1.00]	0.06‡

Value is displayed as mean with standard deviation for continuous variables with normal distribution and as median with interquartile range for continuous non-parametric variables, as mean with standard deviation for continuous variables with normal distribution, and as number with percentage for categorical variables; † One-way ANOVA was done; ‡ Kurskal-Wallis Rank Sum test was done. **Bolt** indicated significance. n=11 were excluded from analysis due to ROM not assessed, or ≤ 3 months post-surgery. *Additional n=3 were excluded from ROM percent of contralateral due to bilateral wrist fractures.

Radiocarpal alignment

On immediate postoperative radiographs, the radiocarpal alignment was abnormal in two cases (2% of the total 87 cases). Of which, one case had a long screw purchase, and one case had a short screw purchase, with no significant difference between the groups (5% versus 1%, p=0.39). Both cases had a small DUC fragment.

At final follow-up radiographs, four additional cases showed loss of radiocarpal alignment, resulting in a total of six (7%) cases: 2 (11%) cases had long screw purchase, and 4 (6%) cases had short screw purchase. There was no significant difference in radiocarpal alignment at follow-up radiographs between cases with long and short screw purchases (p=0.15). Half of the cases had a small DUC fragment, and half had a large one. Finally, in four cases, there was clinically reported DRUJ instability, three having short screw purchase and one long screw purchase. Revision surgery was not performed.

DISCUSSION

Scaffold fixation by inserting a VLP over fracture fragments reduced with a dorsal bone clamp represents a treatment strategy for stabilizing a multi-fragmented intra-articular DRF that avoids independent DUC fixation. In this technique, the dorsal clamp plays a pivotal role by allowing controlled and stable reduction of the dorsal fragments, particularly the DUC, prior to volar plating. This could potentially minimize the need for separate dorsal hardware and may reduce soft-tissue disruption. In this retrospective cohort study, we observed that the final ROM of patients with either long or short screw purchase in the DUC did not differ in ROM outcomes. Similarly, DUC fragment size was not associated with differences ROM outcomes. Furthermore, we observed preserved radial carpal alignment, with no significant difference between short and long screw purchase in the DUC within this cohort, supporting the stabilizing contribution of the dorsal reduction clamp in achieving and maintaining anatomical alignment.

Strengths and limitations

This study should be interpreted considering its strengths and limitations. This study describes outcomes of a cohort treated with a scaffold fixation technique using a VLP, providing insight into this approach for DRFs involving a dorsal-ulnar corner fragment.

It uses a scaffold technique in securing the surrounding fragments and considers that soft tissues are essential to achieve fracture reduction and increase construct strength. In addition, this study included an openly accessible database at ICUC.net® with intra-operative imaging and follow-up information.

A key limitation of this study is the absence of a comparison group. Without a control cohort treated with alternative fixation strategies, such as dorsal plating or fragment-specific fixation, no causal inferences can be made regarding the effectiveness or equivalence of scaffold fixation. The findings should therefore be interpreted as descriptive outcomes of a cohort treated with this technique rather than evidence of superiority or comparative effectiveness. Future research should include comparative studies with appropriate control groups to determine whether scaffold

fixation provides clinically or radiographically meaningful benefits over established fixation strategies, particularly with respect to functional outcomes, radiocarpal alignment, and joint stability.

Secondly, the measurement of radial carpal alignment was retrospectively assessed by one observer on radiographs. The exact position of the wrist on the lateral radiographs can have varied between cases. In addition, the radial carpal alignment can be measured in multiple ways. In this study, we have chosen the method to determine the radial alignment by radiocarpal distance in line with the width of the capitate, showing excellent intra- and inter-observer agreement (25, 26). However, the exact measurement of the capitate-to-axis-of-radius distance was not assessed.

Third, the DRUJ assessment is essential for assessing the wrist's stability—especially in the dorsal-ulnar corner. However, there is no consensus in the research on whether this can be accurately measured using imaging modality (27, 28). Clinical assessment of DRUJ stability is the most reliable method, but it could not be assessed in the study due to its retrospective design. A prospective study with long-term follow-up and serial assessment of DRUJ stability can better assess another aspect of capturing the dorsal ulnar corner with a screw.

Lastly, complication-related outcomes were not evaluated in this study. Although complications such as extensor tendon disorders, infection, nonunion, hardware-related problems, and reoperations are clinically relevant, these events are currently not consistently or systematically registered within the openly accessible ICUC.net® database. As a result, reliable extraction and analysis of complication data were not feasible for the present cohort. Future prospective studies with standardized and dedicated complication reporting are required to more comprehensively assess the safety profile of scaffold fixation.

In addition, this study only included patients with a dorsal-ulnar corner fragment. Future research must include broader cases with different specific fracture fragment patterns to assess whether the scaffold fixation method is accurate and generalizable.

Final ROM

Our study demonstrated adequate restoration of ROM in absolute terms and in relation to the contralateral uninjured wrist motion. Previous studies on the fixation of DRFs with dorsal-ulnar corner fragments have shown comparable or less favorable results concerning both absolute ROM and percentage of the contralateral (29-31). ROM is a crucial clinical outcome from the patient's perspective. This study indicates that the final ROM is not adversely affected when either long or short screw purchase in the dorsal-ulnar corner fragment is used. The results showed comparable outcomes with the non-fractured wrist, suggesting that functional wrist motion can be achieved using this technique in the studied cohort.

Radiocarpal alignment

When fixating a DRF with a dorsal-ulnar corner fragment, it is usually advised to fixate the dorsal-ulnar corner fragment with a long locking screw placed through the VLP, dorsal plate, recontoured plate, fragment-specific fixation, or other adjunct methods (32, 33). The scaffold approach proposed in this study is a new technique that does not focus on the fragment-specific approach advised for comminuted DRFs. In our cohort, radiocarpal alignment was generally preserved; however, loss of alignment was observed in a small subset of cases at final follow-up. Our study did not demonstrate an association between screw purchase length in the dorsal-ulnar corner and radiocarpal alignment. Due to the limited number of malaligned cases, further statistical analysis to identify predictors of loss of alignment was not feasible. Shorter screws that are less likely to cause extensor tendon irritation may be considered with the expectation of similar ROM and maintenance of distal radial alignment. Further research should include comparative studies with an appropriate control group to evaluate the potential clinical and radiographic benefits of this approach.

One study similarly demonstrated that the majority of DRFs fixated by a single VLP achieve union without loss of reduction (34). Additionally, another study indicated that the size of the dorsal-ulnar corner fragment does not indicate the need for a separate dorsal approach in the fixation of a DRF, which also aligns with our findings (35). Furthermore, a study reported that the stability of comminuted DRFs

with volar fragmentation is determined by the reduction of the major fragments and the reduction of the small volar lunate fragment or dorsal-ulnar corner (12). However, this conclusion was a case series based on seven patients with volar shearing fractures. In Beck et al.(31), 52 type B3 DRFs involving the lunate facet were treated with standard VLP, and the incidence of loss of reduction was 13%. One additional study on type B3 DRFs did not show any reduction loss of fractures after VLP (30). Souer et al. (29) conducted a multicenter review of 57 volar marginal rim fractures treated with standard volar plating and noted a 4% reduction loss rate at the final follow-up.

Plating

When treating DRF, using a single VLP with a dorsal bone clamp offers several advantages over multiple plating techniques, particularly in terms of surgical ease, early mobility, and reduced soft tissue complications (36-38). The volar approach is less invasive, minimizing the risk of soft tissue irritation and injury, a common issue with dorsally inserted plates (20, 21, 39). This method simplifies the surgical procedure and promotes faster recovery and rehabilitation. While dorsal locking plates provide direct fracture exposure and benefit specific fracture types like dorsal shear fractures and dorsal die-punch fractures, they come with increased risks of soft tissue problems (40, 41).

In conclusion, this study reports that scaffold fixation was associated with good functional ROM outcomes and generally preserves radiocarpal alignment in a cohort of patients with multi-fragmented intra-articular DRFs, regardless of DUC fragment size. Given the absence of a comparison group, these findings should be interpreted as descriptive rather than evidence of superiority over other fixation methods. Furthermore, screw length did not contribute to the maintenance of DUC stability, especially radiocarpal alignment and DRUJ stability, suggesting that scaffold fixation with VLP, dorsal bone clamp, and shorter screws may be a viable option without compromising radiographic outcomes or ROM in key movement arcs. Future research is needed to evaluate the long-term effects of scaffold fixation on joint stability, particularly regarding distal radioulnar joint (DRUJ) stability, patient-reported outcomes and functional recovery.

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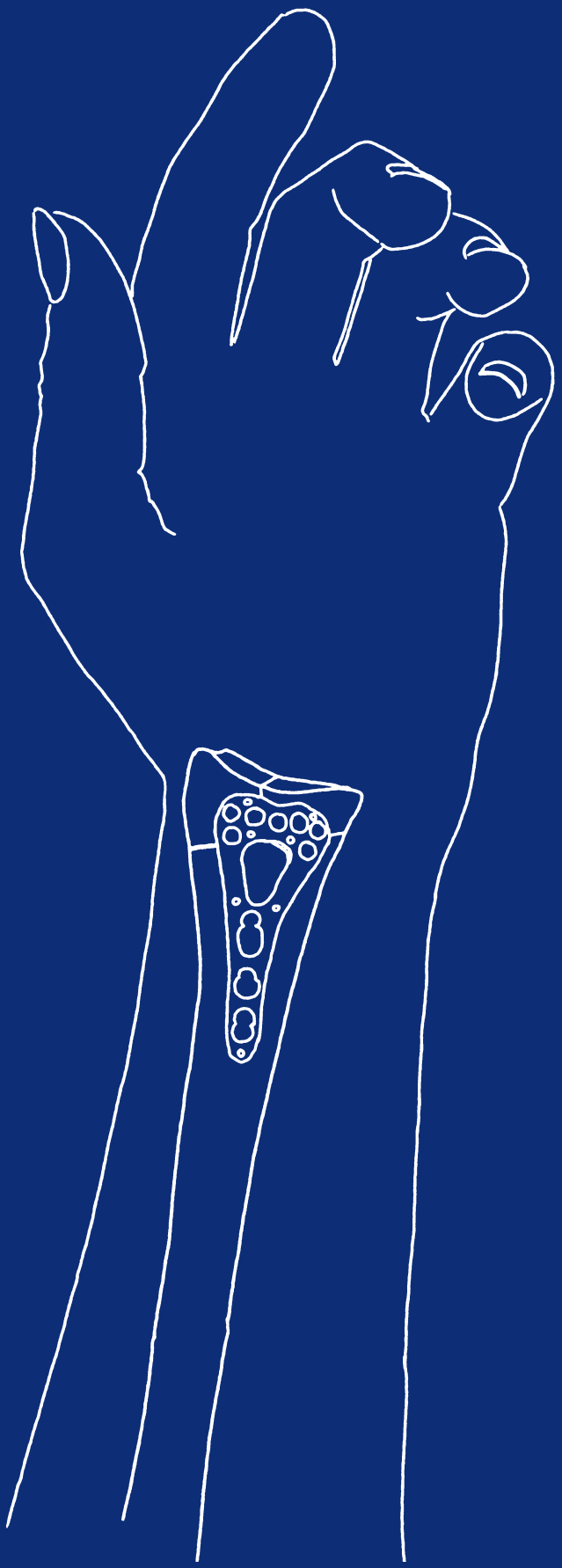

CHAPTER 7

Changes in incidence and indications for implant removal following volar plate fixation of distal radius fractures over 10 years

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ABSTRACT

Purpose

The purpose of this study was 1) to assess volar plate removal rates between 2006-2007 and 2016-2017, and 2) to identify possible changes in indications and risk factors for volar plate removal between those timeframes.

Methods

This is a retrospective cohort study including patients with a distal radius fracture (DRF), requiring open reduction and internal fixation using a volar plate between 2006-2007 (cohort A) and 2016-2017 (cohort B). A total of 756 patients with 771 fractures were included for analysis (cohort A = 377 fractures, cohort B = 394 fractures).

Results

The overall implant removal rate was 7.5% (58/771). Cohort B (9.3%, 37/394) had a higher incidence of implant removal compared to cohort A (5.6%, 21/377 p=0.02). The multivariate analysis showed that patients in cohort B (HR 1.95, 95%CI [1.13-3.37], p=0.016), and cases with intra-articular fracture involvement (HR 3.01, 95% CI [1.20-7.55], p=0.019) were at higher risk of implant removal. The main differences in indications for implant removal were tendon complications, with 33% in cohort A (7/21) and 62% in cohort B (23/37), and intra-articular screw placement, with 33% in cohort A (7/21) and 8% in cohort B (3/37).

Conclusion

An increase in the incidence of implant removal of volar locking plates was shown in DRFs over a ten-year period. A risk factor for implant removal is involvement of the articular surface in the fracture. The main shift in indications for implant removal showed that over time, there is a trend in improved implant and screw placement, but as removal rates still increased, a larger percentage of tendon complications was shown.

INTRODUCTION

Open reduction and internal fixation (ORIF) using a volar plate has become an increasingly popular modality for the management of displaced distal radius fractures (DRF) (1-6). However, complication rates range from 3 to 36%. Complications include tendon irritation and rupture, implant failure, infection, complex regional pain syndrome, other sensibility changes, arthritis, malunion and nonunion (7-9). These complications may result in implant removal, with varying rates in literature between 0 and 100% (5, 6, 10-13).

In response to complications associated with implant prominence and subsequent removal following volar plating of distal radius fractures, orthopedic implant companies have introduced design innovations aimed at mitigating these issues (14, 15). Developments such as low-profile plates and screws are intended to reduce soft tissue irritation, while variable-angle locking screw systems allow for screw placement tailored to individual fracture patterns (16, 17). These advancements aim to enhance implant fit and comfort, potentially decreasing the incidence of implant removal in the late postoperative period. Despite this, Snoddy et al. reported no increase or decrease in distal radius plate removal over five years (10), and longitudinal studies examining these trends over extended timeframes remain limited. Therefore, this study aims to assess volar plate removal rates between 2006-2007 and 2016-2017. In addition, we sought to report and identify risk factors and possible changes in indications for volar plate removal between those time frames.

METHODS

Study design and data collection

This is a retrospective cohort study performed at a multicenter institution, including four hospitals. Approval from the Institutional Review Board was obtained. Current Procedural Technology (CPT®) codes for distal radius fracture fixation were used to extract patients from our database (Supplemental Table S1). We included adult patients (>18 years) with a DRF treated with ORIF using a volar plate at one of our four institutional hospitals between 2006-2007 or 2016-2017. The exclusion criteria were: 1) polytrauma patients with an injury severity score (ISS) of greater than 16; 2) patients with a corrective osteotomy or fracture fixation more than two weeks after distal radius fracture; 3) patients with an open or pathologic fracture; 4) patients fixated with multiple plates or with a non-conventional volar plate (i.e. radial shaft plate, mini fragment plate); 5) patient without any follow-up information after surgery. See Figure 1 for the full inclusion and exclusion flowchart. Patients were grouped into two cohorts: ORIF in 2006-2007 (cohort A) and ORIF in 2016-2017 (cohort B).

Patient and injury characteristics

Two independent researchers (LHMD and CLEL) manually reviewed data from patients' medical files to extract demographic and clinical data. Differences between the collected data were solved in a consensus meeting and, if necessary, resolved by the senior author (NC). The following variables were collected: age at time of injury, sex, dominant side involved, follow-up, smoker at time of injury, diabetes at time of injury, bone density, and the American Society of Anesthesiologists (ASA)-score. If the ASA score was not reported in the patient's medical files, the score was calculated based on the patient's medical history. The following fracture characteristics were collected: intra-articular involvement, AO classification (A, B, C), and concomitant fractures. Only intra-articular involvement was used in further analysis. In addition, the Soong classification was graded for each fracture through X-ray assessment. The primary outcome was whether implant removal occurred (Yes/No), defined as total implant removal, partial removal (only one or more screws), and removal at an outside

institution. The indication for implant removal was recorded as the secondary outcome. Indications for implant removal were categorized as tendon complications (tenosynovitis or rupture), intra-articular screw penetration, implant-related pain, loss of reduction or malunion with revision surgery, and infection.

Statistical analysis

Statistical analyses were performed using R Studio. Descriptive values were described using n (%) and mean with standard deviation (SD) or median with interquartile range (IQR). The Shapiro-Wilk test was performed to define the normality of the data. A 2-sided Fisher's exact test was used to analyze categorical and unpaired t-test or a Wilcoxon rank sum for continuous variables to compare the patient and fracture characteristics of the cohorts. We created a Kaplan-Meier Curve to assess the occurrence of implant removal in both cohorts despite follow-up. Univariate and multivariate Cox proportional hazards regression analyses were conducted to evaluate the association between various predictors and the outcome of interest. Hazard ratios (HRs) with 95% confidence intervals (CIs) were reported for each predictor. A p-value <0.05 was considered statistically significant. Missing data were not imputed.

RESULTS

A total of 1297 patients were extracted from the institutional database using ICD-10 codes (Supplement Table 1). After applying the inclusion and exclusion criteria, 780 DRF in 763 patients were treated with a volar locking plate (Figure 1). In addition, nine patients were excluded due to unavailability of any data, resulting in a total of 754 patients with 771 fractures included for analysis. Data for the following variables were missing: hand dominance in 99 cases, smoker at time of injury in 15 cases, diabetes at time of injury in 4 cases, and Soong-classification in 5 cases.

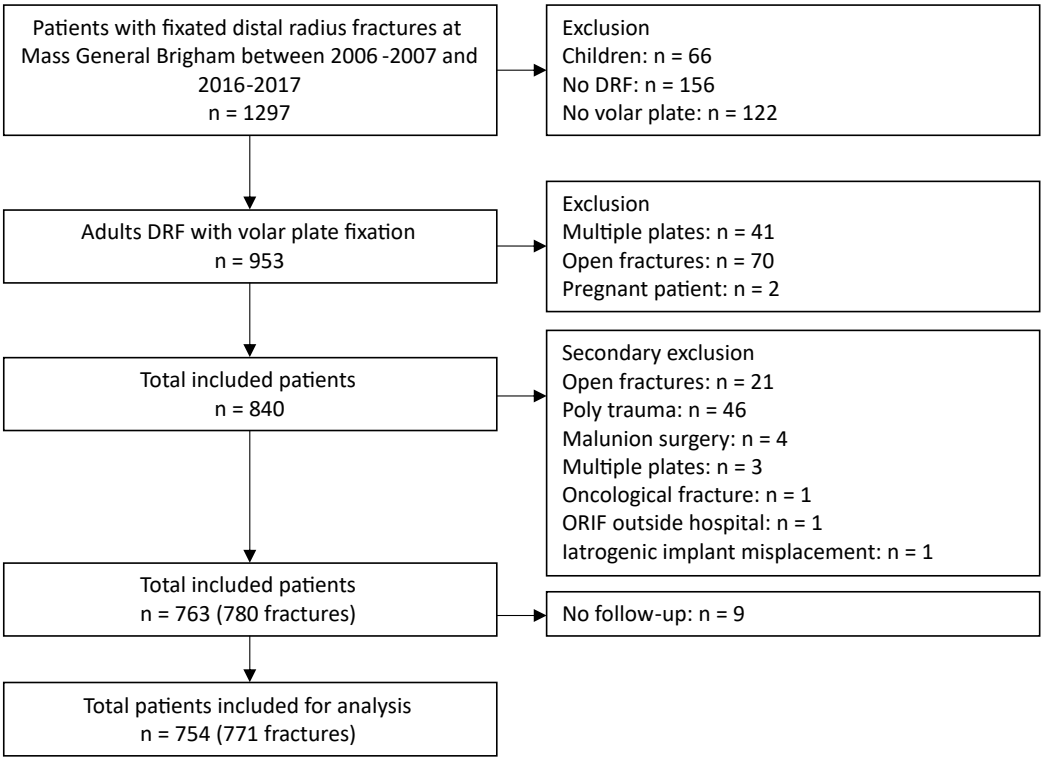


Figure 1. Flowchart of in- and exclusion. DRF: distal radius fracture.

Cohort A (2006-2007) included 377 DRFs, and cohort B (2016-2017) included 394 DRFs. One patient presented in both cohorts due to a second primary distal radius fracture on the contralateral side. The median age at the time of surgery was 54 (IQR 42-66) for cohort A and 58 (IQR 47-66) for cohort B (p=0.08). There were more female patients (76% vs. 68%, p<0.05) and more patients with osteoporosis (21% vs. 12%) or osteopenia (16% vs. 10%) included in cohort B compared to cohort A (p<0.05; Table 1).

For cohort A, the median time to follow-up was 142 weeks (IQR 41-188) and 63 weeks (IQR 18-73) for cohort B (p<0.05; Table 1). Fracture characteristics can be found in Table 2.

Table 1. Patient Characteristics

Variables	Year of surgery cohort			
	All patients (n = 771)	**Cohort A (n = 377)**	**Cohort B (n = 394)**	**P Value**
Age at time of injury, y (median, [IQR])	57 [44-66]	54 [42-66]	58 [47-66]	0.08*
Sex				<0.05**
Female	551 (71%)	253 (67%)	298 (76%)	
Male	220 (29%)	124 (33%)	96 (24%)	
Dominant side involved, n (%)	313 (41%)	130 (34%)	183 (46%)	0.75**
Follow-up, m (median, [IQR])	70 [23-138]	142 [41-188]	63 [18-73]	<0.05*
Smoker at the time of injury				0.09**
Yes	110 (14%)	61 (16%)	49 (12%)	
No	646 (84%)	302 (80%)	344 (87%)	
Diabetes at the time of injury				0.16
Yes	42 (5%)	25 (7%)	17 (4%)	
No	725 (94%)	348 (92%)	377 (96%)	
Bone density				<0.05^
Normal	538 (70%)	292 (78%)	246 (62%)	
Osteopenia	102 (13%)	38 (10%)	64 (16%)	
Osteoporosis	131 (17%)	47 (12%)	84 (21%)	
ASA-score				<0.05**
ASA-1	212 (27%)	120 (32%)	92 (23%)	
ASA-2	485 (63%)	220 (58%)	265 (67%)	
ASA-3	72 (9%)	35 (9%)	37 (9%)	
ASA-4	2 (0.2%)	2 (0.5%)	0	

Value is displayed as median with interquartile range for continuous non-parametric variables, as mean with standard deviation for continuous variables with normal distribution, and as number with percentage for categorical variables; *Wilcoxon Rank Sum test was done; **Fisher's exact test was done. ^Chi-square test was done. Dominant side was unknown in n=99; smoking status was unknown in n=15; diabetes at the time of injury was unknown in n=4.

Implant removal incidence

This study's overall implant removal rate was 7.5% (58/771). A higher incidence of implant removal was found in cohort B (9.4%, 37/394) compared to cohort A (5.6%, 21/377 p=0.02). In cohort A (2006-2007), two had partial implant removal and one had implant removed at an outside institution. In cohort B (2016-2017), all had complete implant removal, and three had implant removal at an outside institution.

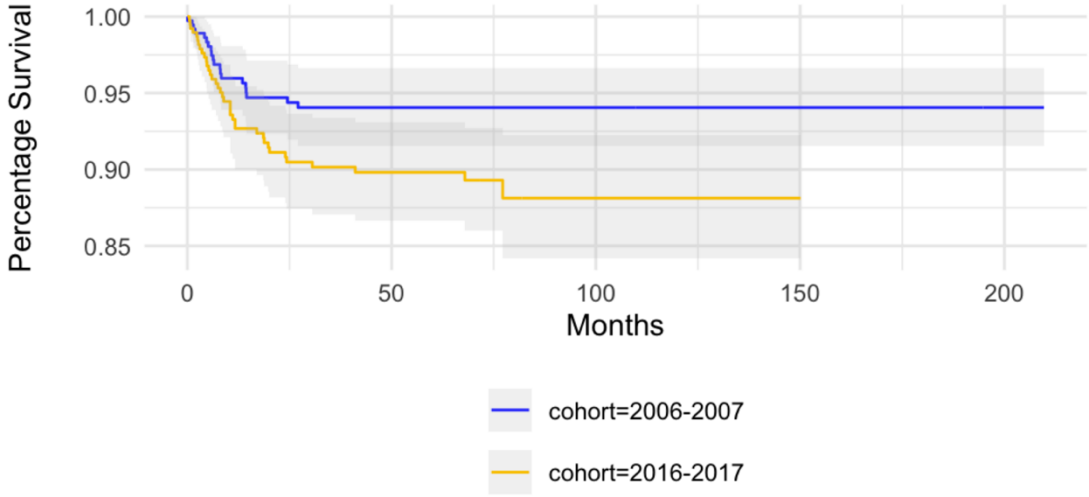
Table 2. Fracture Characteristics

Variables	Year of surgery cohort			
	All fractures (n = 771)	**Cohort A (n = 377)**	**Cohort B (n = 394)**	**P Value**
Intra-articular fractures				0.26
Yes	602 (78%)	301 (80%)	301 (76%)	
No	169 (22%)	76 (20%)	93 (24%)	
AO-classification				0.33^
A	169 (22%)	76 (20%)	93 (24%)	
B	56 (7%)	25 (7%)	31 (8%)	
C	546 (71%)	276 (73%)	270 (68%)	
Soong-classification				**<**0.05**^**
0	317 (41%)	160 (42%)	157 (40%)	
1	389 (50%)	171 (45%)	218 (55%)	
2	60 (8%)	42 (11%)	18 (5%)	
Concomitant fracture	555 (72%)	277 (73%)	278 (71%)	
Ulnar styloid	487 (63%)	253 (67%)	268 (68%)	
Distal ulna	51 (7%)	33 (9%)	18 (5%)	
Scaphoid	25 (3%)	16 (4%)	9 (2%)	
Triquetrum	12 (2%)	6 (2%)	6 (2%)	
Olecranon	9 (1%)	5 (2%)	4 (1%)	
Other	15 (2%)	10 (3%)	5 (1%)	

Value is displayed as median with interquartile range for continuous non-parametric variables, as mean with standard deviation for continuous variables with normal distribution, and as number with percentage for categorical variables; *Wilcoxon Rank Sum test was done; **Fisher's exact test was done. ^Chi-square test was done. Soong classification was not assessed in n=5.

The Kaplan-Meyer curve (Figure 2) shows the rate of implant removal over time. Most implant removals occurred within the first year after DRF fixation. The table below the Kaplan-Meyer curve incorporates patients' loss to follow-up (Figure 2). In only two cases, one in cohort A and one in cohort B, implant removal occurred within 3 weeks after operation. One patient was not included in the Kaplan-Meyer curve because the date of implant removal was uncertain due to removal at an outside institution.

Figure 2. Survival analysis Kaplan-Meyer curve: Removal of Implant - Cohort comparison



cohort=2006-2007					
At Risk	377	276	228	182	43
Events	0	20	20	20	20
cohort=2016-2017					
At Risk	394	244	1	1	0
Events	0	35	37	37	37

Factors associated with risk for implant removal

The univariate analysis showed that cohort B and intra-articular fracture involvement are significantly associated with a higher risk of implant removal (HR: 1.87 (p=0.02), 3.05 (p=0.02), and 2.90 (p=0.02), respectively) (Table 3). The multivariate analysis, including age cohort, articular involvement and Soong-classification, showed that patients in cohort B and cases with intra-articular fracture involvement were at higher risk of getting implant removed (HR 1.96 (95% CI [1.13-3.41], p=0.017, and 3.05 (95% CI [1.21-7.66], p=0.018, respectively) (Table 4).

Table 3. Univariate Cox proportional hazards regression analysis.

	HR	P-value
Age	1.00 (0.98-1.01)	0.62
Sex (Male)	1.16 (0.66-2.04)	0.61
Cohort B (2016-2017)	1.87 (1.08-3.23)	**0.03**
Current Smoker	1.00 (0.48-2.12)	0.99
Bone Density		
Osteopenia	0.55 (0.22-1.4)	0.21
Osteoporosis	0.98 (0.51-1.91)	0.96
ASA (3&4)	0.98 (0.39-2.45)	0.96
Soong Classification		
1	1.58 (0.89-2.79)	0.12
2	1.46 (0.54-3.92)	0.46
Intra-articular fracture	2.90 (1.16-7.25)	**0.02**

HR: Hazard Ratio. Values in parentheses represent 95% Confidence Intervals. **Bolt** indicated significance

Table 4. Multivariate Cox proportional hazards regression analysis, implant removal adjusted for age, intra-articular involvement, and Soong classification

	HR	P-value
Age	0.99 (0.98 -1.01)	0.42
Cohort: B (2016-2017)	1.96 (1.13 – 3.41)	**0.02**
Intra-articular fracture	3.05 (1.21 – 7.66)	**0.02**
Soong-classification 1	1.47 (0.83 – 2.61)	0.18
Soong-classification 2	1.59 (0.59 – 4.31)	0.36

HR: Hazard Ratio. Values in parentheses represent 95% Confidence Intervals. **Bolt** indicated significance

Indications for implant removal

In both cohorts, the primary indication for implant removal was tendon complications, with 7 cases in cohort A (33%, 7/21) with tenosynovitis and 23 cases in cohort B (62%, 23/37) of which 20 (54%, 20/37) had tenosynovitis and 3 (8%, 3/37) tendon rupture (Table 5). Additionally, within cohort A, the presence of an intra-articular screw accounted for implant removal in 7 cases (33%, 7/21), while only 3 cases in cohort B had intra-articular screws (8%, 3/37). Six of these cases had complete implant removal, and one case with single screw removal. In four cases, the exact indication for implant removal was unknown.

Table 5. Indication for implant removal

Indication for implant removal	**2006/2007**	**2016/2017**
N	21	37
Tenosynovitis	7 (33%)	20 (54%)
Tendon rupture	0	3 (8%)
Intra-articular screw penetration	7 (33%)	3 (8%)
Implant related pain	3 (14%)	1 (3%)
Loss of reduction or malunion with revision surgery	2 (10%)	4 (11%)
Infection	1 (5%)	3 (8%)
(Unknown)	1 (5%)	3 (8%)

DISCUSSION

In this study, we surprisingly found an increased incidence of implant removal over a 10-year time span between 2006-2007 and 2016-2017. The primary non-modifiable risk factor for implant removal was intra-articular fracture involvement. The most common indications for volar plate removal were tendon complications and intra-articular screw penetration in 2006-2007, while indications from 2016-2017 were predominantly only due to tendon complications.

Strengths and limitations

This study should be interpreted in light of its strengths and limitations. The strength of this study is the independent data collection by two researchers and collection at the same institutions, thereby accounting for potential unobserved confounding secondary to regional treatment bias. This ensured consistency and reduced missing values and potential bias, strengthening the reliability of the findings.

The primary limitation is the retrospective study design, which includes issues such as missing data, variability in documentation, and interpretation of notes. Moreover, the exact indication for the removal of implant was unknown or not further specified for some cases, contributing to variability in the reported indications for removal.

Second, implant removal may have occurred in patients who were lost to follow-up. However, our survival analysis includes all available data up to the last known follow-up. Additionally, we included patients with documentation of implant removal at another healthcare center; however, this may lead to an underestimation of the exact implant removal rate. Given the comparability of both groups, this is not expected to have affected the two cohorts differently. Furthermore, we only excluded cases without any form of follow-up data to ensure early postoperative incidents were captured. This provides a comprehensive overview and a more accurate estimation of survival times and implant removal incidence. There remains a possibility that patients who sought care elsewhere for implant removal were missed, potentially leading to an underestimation of the actual implant removal rates. Given the

comparability of both groups, this is not expected to have affected the two cohorts differently.

Third, we collected all implant removals for both early and late complications. This may introduce some variability, however, it is applied consistently across both cohorts and therefore should not affect the primary outcome. Furthermore, in only two cases, implant removal occurred within 3 weeks post-surgery. We did not systematically collect data on plate characteristics. However, during the study period, volar locking plates from different manufacturers were used at the discretion of the treating surgeon.

Increased incidence

In this study, we observed a significant increase from 5.6% to 9.4% in implant removal over the past decade, with an overall incidence of 7.5%. This aligns with previous and recent reported removal rates ranging from 8.5% to 11.2% (6, 8, 18, 19). An initial comparison with the data from 2006-2007 suggested a minor increase in these incidences. However, the Kaplan–Meier analysis and multivariate models shown in this study, which provide a more robust longitudinal estimation, revealed a significant rise in implant removal, with a notably elevated risk in the more recent cohort (cohort B). These findings underscore that implant removal has become more common in recent years.

The survival analysis in our study revealed that most implant removals occurred within the first year post-surgery, a trend consistent with findings from Holc et al. (18) and Palola et al. (15), who reported that 87.3% of implant removals were performed within this time frame. These results indicate that the first year post-op is a 'high-risk period' for removing implants, underscoring the importance of close patient monitoring to identify early signs of complications. Regular follow-up and proactive management may help reduce delays in necessary reoperation. However, implant removal is not without risks. Complications are reported in approximately 10% (20) (21). Therefore, individuals should be counseled about potential symptoms and encouraged to promptly report any discomfort or restricted mobility.

The increase in this incidence in this study can be explained based on a few theories outlined below. In recent years, a shift has occurred in patient expectations regarding postoperative function and discomfort (13). This, combined with the growing emphasis on patient-centered care and shared decision-making, may have led to an increased demand for implant removal. In addition, patients and doctors are more involved in monitoring potential complications, such as stiffness, pain, or irritation, and may be more likely to opt for implant removal when faced with these issues (22-25).

Surgeons might be more conservative with regard to leaving plates in place, particularly in younger or more active patients who are more likely to experience long-term irritation from implants. However, our study showed no association between age and risk of implant removal. Furthermore, reports of tendon complications after volar plating emerged around 2006 (26-28). As a result, there may have been a shift toward removing implant as a preventative measure after fracture healing to reduce the risk of complications and to potentially improve functional outcomes (29, 30). However, this was not directly captured in our analysis. Plate selection was not standardized and left to the discretion of the treating surgeon.

Another explanation for the increase in implant removal observed over the past decade may be related to changes in healthcare policy and reimbursement structures. The Affordable Care Act (ACA), enacted in 2010, expanded insurance coverage through individual mandates and Medicaid eligibility, reducing financial barriers and improving access to elective procedures such as implant removal (29). In parallel, Medicare reimbursement data suggest that while payments for most orthopedic procedures declined in real terms between 2006 and 2016, reimbursement for implant removal remained stable or even increased slightly (31). This shift may have made implant removal relatively more financially attractive for providers.

The increasing use of high-resolution imaging (CT or MRI) to plan secondary procedures or evaluate implant positioning may also have contributed to higher detection of implant-related concerns and, thus, more frequent removals. Finally, extrapolation of our findings should be done with caution, as healthcare systems vary internationally, particularly between Europe and the United States, where differences

in reimbursement, cost structures, and surgical practice norms may significantly impact decision-making around implant removal.

Factors associated with increased risk of implant removal

In this study, we observed that an intra-articular fracture was a risk factor for implant removal. Intra-articular fractures are more challenging to fixate, potentially increasing the likelihood of implant complications. This can be related to an increased likelihood of improper implant placement, difficulty achieving reduction, or stress on the articular surface (32, 33).

Soong et al. developed a grading system to evaluate the placement of volar locking plates and suggested that poor plate positioning could be related to implant removal (10, 34). However, this is an ongoing debate in literature (6, 10, 18, 19). This study found no association between Soong's grade and the likelihood of implant removal. In our study, fewer plates were classified as Soong Grade 2 in cohort B, likely reflecting increased awareness of potential complications associated with prominent plate positioning. Despite this, cohort B showed a higher rate of tendon irritation and implant-related complications. This apparent discrepancy may stem from multiple contributing factors beyond plate prominence alone. Furthermore, recent work has questioned the continuous predictive value of the Soong classification, suggesting instead that the primary predictive distinction lies between Grade 2 and non-Grade 2 positioning (35). This may help explain the lack of association between Soong grade and implant removal in our cohort.

Indications for implant removal

Tenosynovitis or tendon rupture and intra-articular screw placement were the most common indication for implant removal in this study, which is in line with literature (8, 10, 18). It is noticeable that in more recent years, the increased number of plate removals can mainly be attributed to tenosynovitis. This trend may be explained by the fact that tendon complications began to be reported around 2006, corresponding to the early years included in this study (26-28). It is necessary to remove an implant when symptomatic prominence of plates or screws occurs (8). However, a previous

study has shown that highly frequent plate removal does not contribute to better clinical outcomes (13). Another previous study reported that flexor tendon rupture occurred within 6-26 months post-surgery (36). Considering this, early detection of these symptoms is necessary to give a good and clear indication for possible removal and improvement of wrist function and to decrease further complications. Notably, our study found that in the more recent cohort (cohort B), intra-articular screw misplacement was a less frequent cause of implant removal. This finding suggests that surgeons have improved in accurate screw positioning in recent years and the potential influence of variable angle plate development. In future research, incorporating patient-reported outcomes can provide valuable insights into the long-term impact of implant removal on function and patient satisfaction. This may aid in decision-making regarding the necessity of removal in individual patients.

Conclusion

In conclusion, this study showed an increase in the incidence of implant removal of volar locking plates in DRFs over a ten-year period, showing most implant removal occurring in the first year post-surgery. The risk for implant removal was associated with intra-articular fractures. The main shift in indication for implant removal was from intra-articular screw placement in 2006-2007 towards tenosynovitis in 2016-2017.

Supplement Table 1. ICD-10 codes

Code	Description
S63.51	Sprain of carpal joint
S63.59	Other specified sprain of wrist
S63.50	Unspecified sprain of wrist
S63.8X	Sprain of other part of wrist and hand
S63.9	Sprain of unspecified part of wrist and hand
S63.09	Other subluxation and dislocation of wrist and hand
S63.00	Unspecified subluxation and dislocation of wrist and hand
S63.39	Traumatic rupture of other ligament of wrist
S63.30	Traumatic rupture of unspecified ligament of wrist
S69.8	Other specified injuries of wrist, hand and finger(s)
M25.34	Other instability, hand
M25.33	Other instability, wrist
M25.53	Pain in wrist

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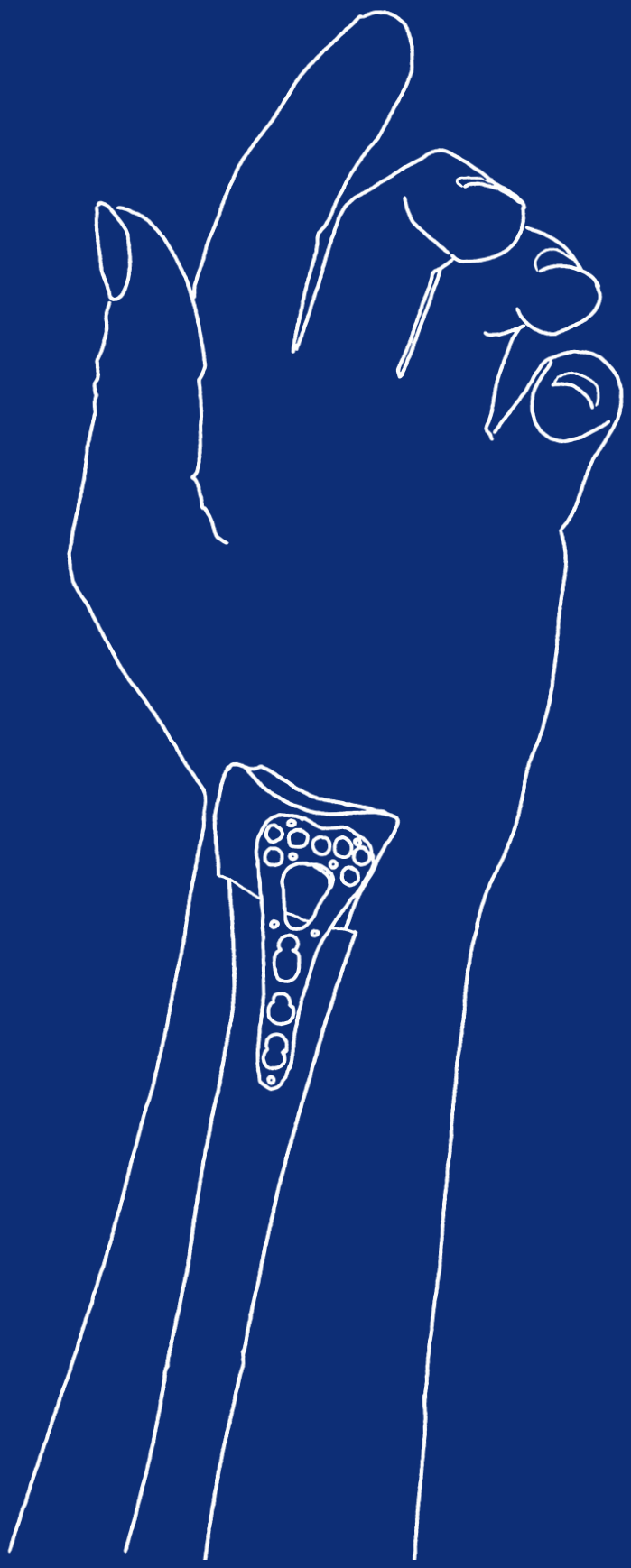

CHAPTER 8

Factors associated with reoperation after distal radius nonunion repair

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ABSTRACT

Purpose

This study aimed to evaluate the incidence of, and factors associated with, reoperation after distal radius nonunion repair.

Methods

We conducted a retrospective cohort study at a multicenter academic institution and identified adult patients who underwent open reduction and internal fixation for distal radius nonunion between January 2005 and August 2021. Thirty-three patients were included in this study. The cohort consisted of 13 males (13/33) and had a median age of 56 years (interquartile ranges: 49-64). Median follow-up was 59 months (interquartile ranges: 23-126).

Results

Unplanned reoperations occurred in eight of 33 patients. The most common reasons for reoperation were irrigation and debridement for infection, revision surgery for persistent nonunion, and unplanned hardware removal. In total, 10 complications occurred in nine patients. The most common complications were infection and persistent nonunion; both occurred in three cases.

Conclusion

Complications after distal radius nonunion repair are common. Reoperation after distal radius nonunion repair is required in approximately one of four cases.

INTRODUCTION

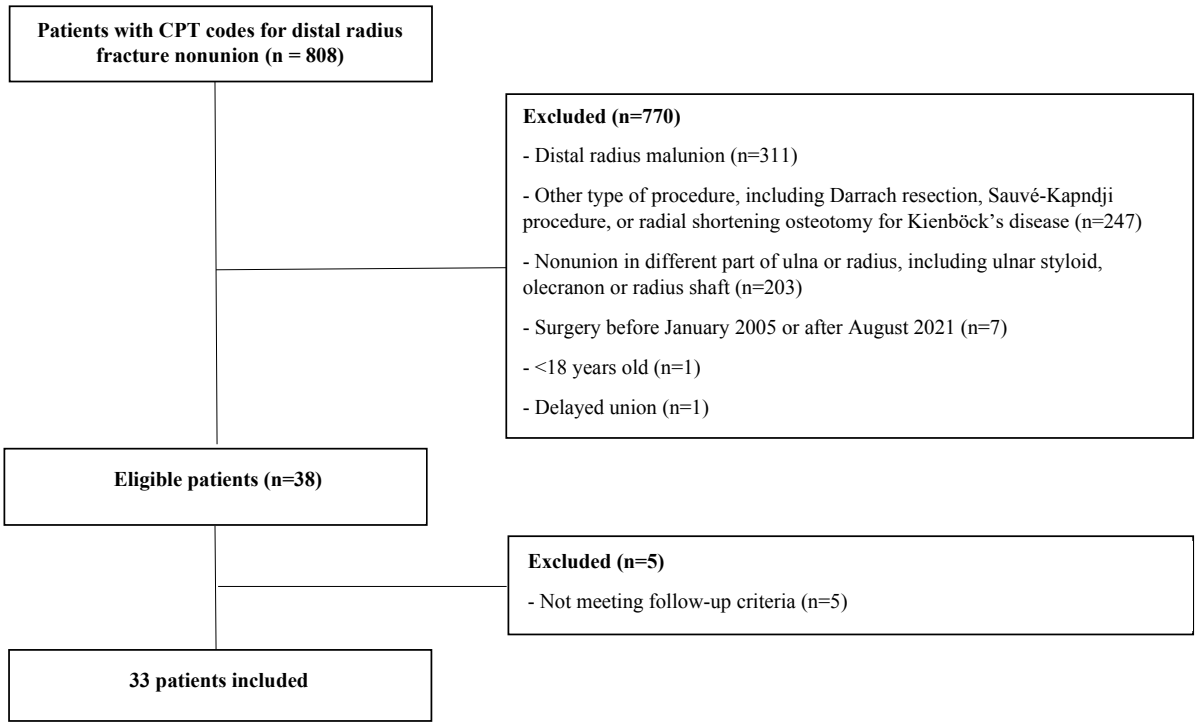
Nonunion after distal radius fracture or osteotomy for distal radius malunion is challenging to treat (1–3). The incidence of symptomatic nonunion after a distal radius fracture varies between 0.2% and 1.3% (4, 5), and may lead to substantial loss of hand and wrist function (2, 3, 6, 7).

Published surgical results for distal radius nonunion repair are limited. There are several technical reports and case series, but these are necessarily limited by small sample size, ranging from five to 23 patients (2, 3, 7–10). More information from larger studies regarding reoperation and complication rates after nonunion repair would be helpful when counseling patients about expected outcomes. Therefore, the primary aim of our study was to assess reoperation after open reduction and internal fixation (ORIF) for distal radius nonunion, and secondarily to describe factors that may be associated with reoperation.

METHODS

This is a descriptive retrospective cohort study performed at a multicenter academic institution. After Institutional Review Board approval, we identified 808 patients from our database using CPT codes related to distal radius nonunion repair between January 2005 and August 2021 (Supplemental table S1). We used a broad spectrum of CPT codes to identify all patients. From these 808 patients, 38 were eligible based on our inclusion criteria: adult patients (≥18 years old) who underwent ORIF for a distal radius nonunion at one of our institution's hospitals (Figure 1). This study did not involve patients who underwent partial or complete wrist arthrodesis for their nonunion, nor did it include patients converted to wrist arthroplasty. Patients were followed until one of the following criteria were met: discharge from follow-up (n= 7), reoperation (n=8), or 18 months of follow-up since the initial nonunion surgery (n=18). Five patients did not meet these follow-up criteria, with a median follow-up of one month (range 0-5). They were therefore excluded from the analysis, resulting in a final cohort of 33 patients.

Figure 1. Flow-chart of inclusion and exclusion criteria



Electronic medical chart review was performed to collect demographic information, past medical history, and injury- and surgery-related variables (Table 1, 2 and 3). The data were independently collected by two authors (MS, LD). Any discrepancies were addressed in a consensus meeting, or when necessary, with consultation of the senior authors (CL/ARB). The primary outcome was reoperation.

Nonunion was defined as: 1) no radiological signs of bridging callus of at least three out of four cortices six months after surgery, or 2) if surgical intervention for nonunion was performed (2, 11). Reoperation was defined as any subsequent complication-related surgical intervention on the ipsilateral wrist. The secondary outcome included postoperative complications (Table 3).

Five types of complications were recorded: infection, persistent nonunion, graft site fracture, acute carpal tunnel syndrome, and extensor tendonitis. Graft site fracture was defined as a spontaneous cortical defect on a postoperative radiograph extending into the graft site or if a spontaneous graft site fracture was documented. Acute carpal tunnel syndrome was defined as newly progressive numbness and pain in the median nerve distribution over hours to days following nonunion surgery, requiring release (12). Extensor tendonitis was defined as symptoms of pain, crepitus, or irritation of the extensor tendons adjacent to hardware, occurring postoperatively in the ipsilateral wrist as described by the surgeon.

To expose the nonunion site, a volar or dorsal approach was chosen, depending on the direction of angulation and the location of the initially implanted hardware. The nonunion was treated with either ORIF or bone grafting only, depending on the stability of the nonunion and the fixation of the initially implanted hardware.

Statistical Analysis

Reoperation rate was described using frequency and percentage. We provided the characteristics of patients with a reoperation and patients without a reoperation after nonunion repair. The normality of the distribution of the data was assessed using the Shapiro-Wilk test. We presented frequencies and percentages (n, %) with 95% confidence interval (95%CI) for categorical data, and medians and interquartile ranges

(IQR) for continuous data. Less than 10% of data were missing for body mass index (BMI), dominant hand involved and tobacco use (Table 1). Missing values were omitted. The two-sample test of proportions was used to calculate the confidence intervals of the reoperation rates. In addition, we performed a post-hoc power analysis using GPower 3.1. All comparisons were underpowered, meaning that the sample size was insufficient to detect a statistically significant effect.

RESULTS

Study sample

The 33 analyzed patients consisted of 13 males (13/33) with a median age of 56 years (interquartile range (IQR) 49-64; Table 1). Of the patients in this cohort, eight were smokers (8/31; Table 1). Four of the 33 cases were a hypertrophic nonunion, and the remainder were oligotrophic or atrophic (4/33; Table 2). Three patients had a known infection prior to nonunion surgery (3/33; Table 2). All patients received antibiotics, two patients had additional surgical debridement, and one patient underwent a single-stage surgery. The median time from distal radius fracture to nonunion surgery was eight months (n=29, IQR 4-15). Both the reoperated group (n=7, IQR 2-15) and the non-reoperated group (n=22, IQR 4-18) had a median time from distal radius fracture to nonunion surgery of eight months. The median follow-up time for this cohort was 59 months (IQR 23-126).

Table 1. Patient demographics

Variables	Overall (N=33)	Reoperation (N=8)	95% ci	No reoperation (N=25)	95% CI
Sex					
male	13 (39%)	5 (38%) 3	12%-65%	8 (62%)	35%-88%
female	20 (61%)	(15%)	0%-31%	17 (85%)	69%-100%
Age	56 (49-64)	49 (46-51)		60 (51-65)	
BMI (N=31)	30.2 (25.5-36.0)	29.5 (25.1-31.7)		30.5 (26.0-36.4)	
Tobacco use (N=31)	8 (26%)	4 (50%)	15%-85%	4 (50%)	15%-85%
No tobacco use	23 (74%)	4 (17%)	2%-33%	19 (83%)	67%-98%
Total	31 (100%)	8 (26%)		23 (74%)	
Diabetes	2 (6%)	1 (50%)	0%-100%	1 (50%)	0%-100%
No diabetes	31 (94%)	7 (23%)	8%-37%	24 (77%)	63%-92%
Total	33 (100%)	8 (24%)		25 (76%)	
Inflammatory arthritis	2 (6%)	0 (0%)	NA	2 (100%)	NA
No inflammatory arthritis	31 (94%)	8 (26%)	10%-41%	23 (74%)	59%-90%
Total	33 (100%)	8 (24%)		25 (76%)	
Osteoarthritis	17 (52%)	2 (12%)	0%-27%	15 (88%)	73%-100%
No osteoarthritis	16 (48%)	6 (38%)	14%-61%	10 (62%)	39%-86%
Total	33 (100%)	8 (24%)		25 (76%)	
Steroid use	2 (6%)	0 (0%)	NA	2 (100%)	NA
No steroid use	31 (94%)	8 (26%)	10%-41%	23 (74%)	59%-90%
Total	33 (100%)	8 (24%)		25 (76%)	
Dominant hand involved (n=31)	15 (48%)	4 (27%)	4%-49%	11 (73%)	51%-96%
Non-dominant hand involved	16 (52%)	4 (25%)	4%-46%	12 (75%)	54%-96%
Total	31 (100%)	8 (26%)		23 (74%)	
Previous ipsilateral fracture	1 (3%)	0 (0%)	NA	1 (100%)	NA
No previous ipsilateral fracture	32 (97%)	8 (25%)	10%-40%	24 (75%)	60%-90%
Total	33 (100%)	8 (24%)		25 (76%)	
Follow-up in months	59 (23-126)	49.5 (30-112)		73 (13-147)	
Time from distal radius fracture to nonunion surgery (N=29)	8 (4-15)	8 (2-15)		8 (4-18)	
Time from index surgery to nonunion surgery (N=15)	8 (6-19)	7.5 (4.5-11.5)		8 (5-24)	

Data are shown as n(%), and median (interquartile range)
for variables with missing data, the number of available observations is given in brackets
BMI, body mass index; CI, confidence interval; NA, not applicable.

Reoperations

Nonunion surgery involved a volar approach in 27 patients (27/33) and a dorsal approach in six patients (6/33). Plate constructs that were used included volar plates in most patients (24/33; Figure 2), followed by multiple plates (5/33), a dorsal spanning plate (1/33), and a radial shaft plate (1/33).

For the subgroup of patients who had multiple plates placed, two mini fragment plates on the volar side, a volar locked plate in combination with a radial column plate, and a L-plate on the volar side in combination with a radial column plate were used. Regarding graft type, autograft was used in 23 patients (23/33), allograft in two patients (2/33), a combination of autograft and allograft in two patients (2/33); a bone substitute was used in one patient (1/33). Five patients did not receive any type of graft (5/33). The 25 autografts consisted of 13 iliac crest grafts, six distal ulna grafts, four distal radius grafts, one proximal radius shaft graft, and one olecranon graft.

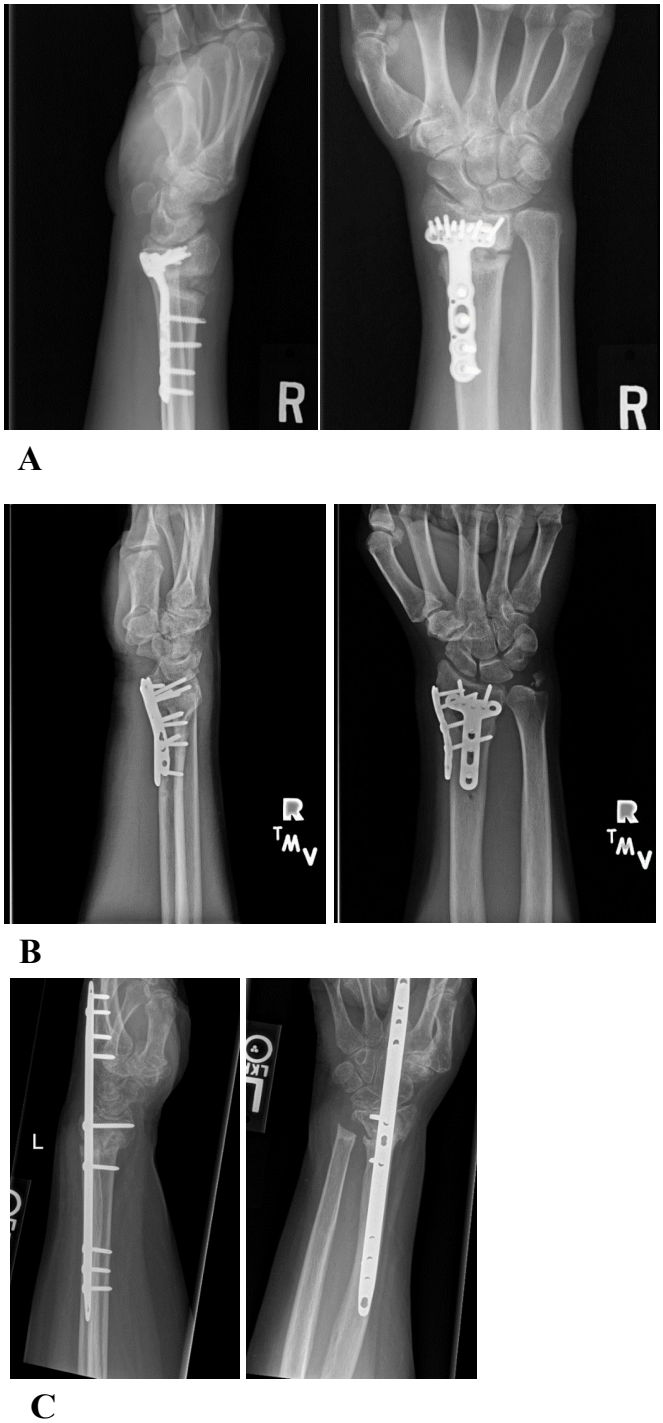


Figure 2. Radiographs of plate constructs. **A.** Volar plate; **B.** Multiple plates; **C.** Dorsal spanning plate

Unplanned reoperations occurred in eight of 33 patients (Table 3). The median time to reoperation was eight months (IQR: 0.5-10.5). Reasons for reoperation were irrigation and debridement (I&D) for infection (3/33), revision surgery for persistent nonunion (2/33), unplanned hardware removal (2/33), and release for acute carpal tunnel syndrome (1/33). One patient had a superficial wound infection treated with I&D. Another patient had positive wound cultures, without osteomyelitis. The third patient was treated with debridement for osteomyelitis prior to nonunion surgery and developed signs of infection after surgery, requiring I&D. Hardware was removed due to plate loosening and prominent hardware in the distal-radioulnar joint. Other reasons for reoperation are described in Table 3. Three patients
(3/33) underwent a second reoperation. One patient required a second I&D without hardware removal, another patient required hardware removal after a prior I&D, and one patient developed an infection after revision surgery for persistent nonunion and underwent I&D without hardware removal.

Two of five patients without any type of graft required reoperation, whereas four of the 23 with autograft, one of the two with allograft, none of the two with autograft/allograft and the one patient with bone substitute needed reoperation. Of the patients with persistent nonunion, one was treated with a volar plate without any graft, another patient received a volar plate with an allograft, and the third patient underwent nonunion surgery with a radial shaft plate without any graft.

Four of the eight patients who used tobacco required reoperation, while four of the 23 patients who did not use tobacco required reoperation. All three patients with an initially infected nonunion required reoperation. Two underwent reoperation due to infection and the third required reoperation for acute carpal tunnel syndrome.

Complications

We identified 10 complications (including reoperation) in nine patients after distal radius nonunion repair (9/33; Table 3). More specifically, eight patients (8/33) developed one complication, and one patient (1/33) developed two complications. Complications were infection (3/33), persistent nonunion (3/33), spontaneous iliac crest graft site fracture (2/33), extensor tendonitis (1/33), and acute carpal tunnel

syndrome (1/33). The diagnosis of acute carpal tunnel syndrome was made two days after surgery. Of the three persistent nonunion cases, one had an infection. One patient with persistent nonunion was treated non-operatively but followed up for the persistent nonunion at an outside hospital. The two spontaneous graft site fractures were treated non-operatively with non-weight-bearing advice only. In addition, three patients reported some sensory disturbances post-operatively. One experienced transient numbness in the palm of the hand, and two patients had altered sensation over the dorsal aspect of the hand. The latter was attributed to a tight splint.

Table 2. Fracture and surgery characteristics

Variables	Overall (n=33)	Reoperation (n=8)	95% CI	No reoperation (n=25)	95% CI
Open Fracture	8 (24%)	3 (38%)	4%-71%	5 (62%)	29%-96%
Closed Fracture	25 (76%)	5 (20%)	4%-36%	20 (80%)	64%-96%
Total	33 (100%)	8 (24%)		25 (76%)	
AO Classification*					
A	9 (38%)	1 (11%)	0%-32%	8 (89%)	68%-100%
B	1 (4%)	0 (0%)	NA	1 (100%)	NA
C	14 (58%)	4 (29%)	5%-52%	10 (71%)	48%-95%
Total	24 (100%)	5 (21%)		19 (79%)	
Concomitant fracture	24 (73%)	4 (17%)	2%-32%	20 (83%)	68%-98%
No concomitant fracture	9 (27%)	4 (44%)	12%-77%	5 (56%)	88%-23%
Total	33 (100%)	8 (24%)		25 (76%)	
Nonunion concomitant fracture	18 (75%)	2 (11%)	0%-26%	16 (89%)	74%-100%
Union concomitant fracture	6 (25%)	2 (33%)	0%-71%	4 (67%)	29%-100%
Total	24 (100%)	4 (17%)		20 (83%)	
Infected nonunion	3 (9%)	3 (100%)	NA 3%-30%	0 (0%)	NA 70%-
No infected nonunion	30 (91%)	5 (17%)		3 (83%)	97%
Total	33 (100%)	5 (24%)		28 (76%)	
Hypertrophic nonunion	4 (12%)	0 (0%)	NA 11%-44%	4 (100%)	NA 56%-
Other nonunion type	29 (88%)	8 (28%)		21 (72%)	89%
Total	33 (100%)	8 (24%)		25 (76%)	
Initial fracture treatment					
Surgery	17 (52%)	4 (24%)	3%-44%	13 (76%)	56%-97%
Conservative management	16 (48%)	4 (25%)	4%-46%	12 (75%)	54%-96%
Total	33 (100%)	8 (24%)		25 (76%)	
Initial fixation method					
Volar plate	12 (71%)	2 (17%)	0%-38%	10 (83%)	62%-100%
External fixation	4 (23%)	1 (100%)	0%-67%	3 (25%)	33%-100%
Dorsal bridge plate	1 (6%)	1 (75%)	NA	0 (0%)	NA
Total	17 (100%)	4 (24%)		13 (76%)	

Table 2. Fracture and surgery characteristics

Variables	Overall (n=33)	Reoperation (n=8)	95% CI	No reoperation (n=25)	95% CI
Nonunion after distal radius corrective osteotomy	9 (27%)	3 (33%)	3%-64%	6 (67%)	36%-97%
Nonunion after other treatment for distal radius fracture	24 (73%)	5 (24%)	5%-37%	19 (76%)	63%-95%
Total	33 (100%)	8 (24%)		25 (76%)	
Surgical approach					
Volar	27 (82%)	6 (22%)	7%-38% 0%-	21 (78%)	62%-93%
Dorsal	6 (18%)	2 (33%)	71%	4 (67%)	29%-100%
Total	33 (100%)	8 (24%)		25 (76%)	
Surgical method					
ORIF	26 (79%)	7 (27%)	10%-44%	19 (73%)	56-90%
Bone grafting**	7 (21%)	1 (14%)	0%-40%	6 (86%)	60%-100%
Total	33 (100%)	8 (24%)		25 (76%)	
Plate type					
Volar plate	24 (77%)	6 (25%)	8%-41%	18 (75%)	59%-92%
Multiple plates	5 (16%)	1 (20%)	0%-55%	4 (80%)	45%-100%
Dorsal spanning plate	1 (3%)	0 (0%)	NA	1 (100%)	NA
Radial shaft plate	1 (3%)	1 (100%)	NA	0 (0%)	NA
Total	31 (100%)	8 (26%)		23 (74%)	
Graft use					
No graft	5 (15%)	2 (40%)	0%-83%	3 (60%)	17%-100%
Allograft	2 (6%)	1 (50%)	0%-100%	1 (50%)	0%-100%
Autograft	23 (70%)	4 (17%)	2%-33% NA	19 (83%)	67%-98%
Autograft + Allograft	2 (6%)	0 (0%)	NA	2 (100%)	NA
Artificial bone substitute	1 (3%)	1 (100%)	NA	0 (0%)	NA
Total	33 (100%)	8 (24%)		25 (76%)	

Data are shown as n(%)

* 9 patients underwent malunion surgery before the nonunion surgery and were therefore not categorized in the AO classification

** 2 patients had bone grafting without ORIF and 5 patients retained their volar plate during nonunion repair

AO Classification, Arbeitsgemeinschaft für Osteosynthesefragen Classification; CI, Confidence interval; NA, not applicable; ORIF, Open Reduction Internal Fixation

DISCUSSION

This retrospective cohort study aimed to evaluate reoperation rates, and potential factors associated with reoperation after nonunion surgery. In our study, a reoperation was performed in eight of the 33 patients who underwent distal radius nonunion surgery. This is similar to one study with a reoperation rate of 22% (10), whereas other studies found unplanned reoperation rates between 0-60% (2, 3, 7, 9). The wide complication range can be explained by small sample sizes.

Types of unplanned reoperation in our study included I&D for infection, revision surgery for persistent nonunion, hardware removal, and acute carpal tunnel release. Our reoperations partially correspond with previous literature (2, 9, 10). Additionally, arthroplasty and total wrist arthrodesis for persistent nonunion have been used as a salvage operation although none of the patients in our cohort required these procedures (9, 10).

Knowledge about factors associated with reoperation after distal radius nonunion surgery is limited. In our cohort, four of the eight smokers and four of the 23 non-smokers required a reoperation. In a study by Smith et al., all five patients with a distal radius nonunion were heavy tobacco users (9). In studies discussing reoperation after nonunion in other bones, smoking also appeared to be a risk factor for failure of surgery (13–17). In addition, we found that all three patients with an initially infected nonunion required reoperation. Previously, presence of infection has been shown to negatively influence consolidation of nonunion (16).

Nine of the 33 patients in our study experienced one or more complications after nonunion surgery, while previously reported complication rates varied between 0% and 27% (2, 3, 7, 10). Two of the five patients in our study who did not receive a graft at their initial nonunion surgery developed a nonunion. The third patient with persistent nonunion was one of two who received solely an allograft during nonunion surgery. None of the patients with an autograft or both allograft and autograft developed persistent nonunion. Previous studies show that the use of an autograft reduces the risk of developing nonunion when compared to no graft or to allograft in patients undergoing corrective osteotomy of the distal radius and other long bones (1, 18). This suggests that it is important to weigh the benefits of using an autograft against

the risks for graft site morbidity.

The findings of this study should be interpreted with respect to its limitations. The retrospective design has limitations in terms of missing data, and precision and interpretation of documentation. This included information on whether grafts were utilized for structural or biologic reasons. This may result in possible underestimation of the effect of certain variables. In addition, we defined nonunion as either no bridging > six months after fracture or surgery or an operation performed for nonunion based on the surgeon's evaluation of a potential distal radius nonunion. The latter one may have introduced diagnostic inaccuracies regarding nonunion. Eleven patients underwent nonunion surgery < six months after distal radius fracture, with the surgeries being performed between two and 54 months after the fracture occurred. Furthermore, we were unable to accurately assess bone demineralization, however osteoporosis does not seem to be a risk factor for the development of nonunion (19). Although we classified hypertrophic nonunions, we did not separately categorize atrophic and oligotrophic nonunions. Nonetheless, the non-hypertrophic nonunion types, atrophic and oligotrophic, suggest the same biologic origin (20). Considering the amounts of grafts used in this study, it can be assumed that all types of nonunion were treated with the intention to address the underlying cause of the nonunion. Moreover, patients may have been followed up at other healthcare institutions, resulting in a potential underestimation of reoperation and complication rates. However, we attempted to mitigate this factor by excluding patients with less than 18 months of follow-up, and without discharge of follow-up. The sample size was small; therefore, covariates could not be assessed using comparable analysis and the reported numbers should be considered carefully. Finally, we only considered ORIF for nonunion surgery and we did not assess outcomes of salvage procedures like arthrodesis or arthroplasty.

In conclusion, reoperation was required in one out of four patients who underwent distal radius nonunion surgery and complications were common. Infection and nonunion were the most frequent complications. These results can provide information to aid with counseling patients about risks of distal radius nonunion surgery.

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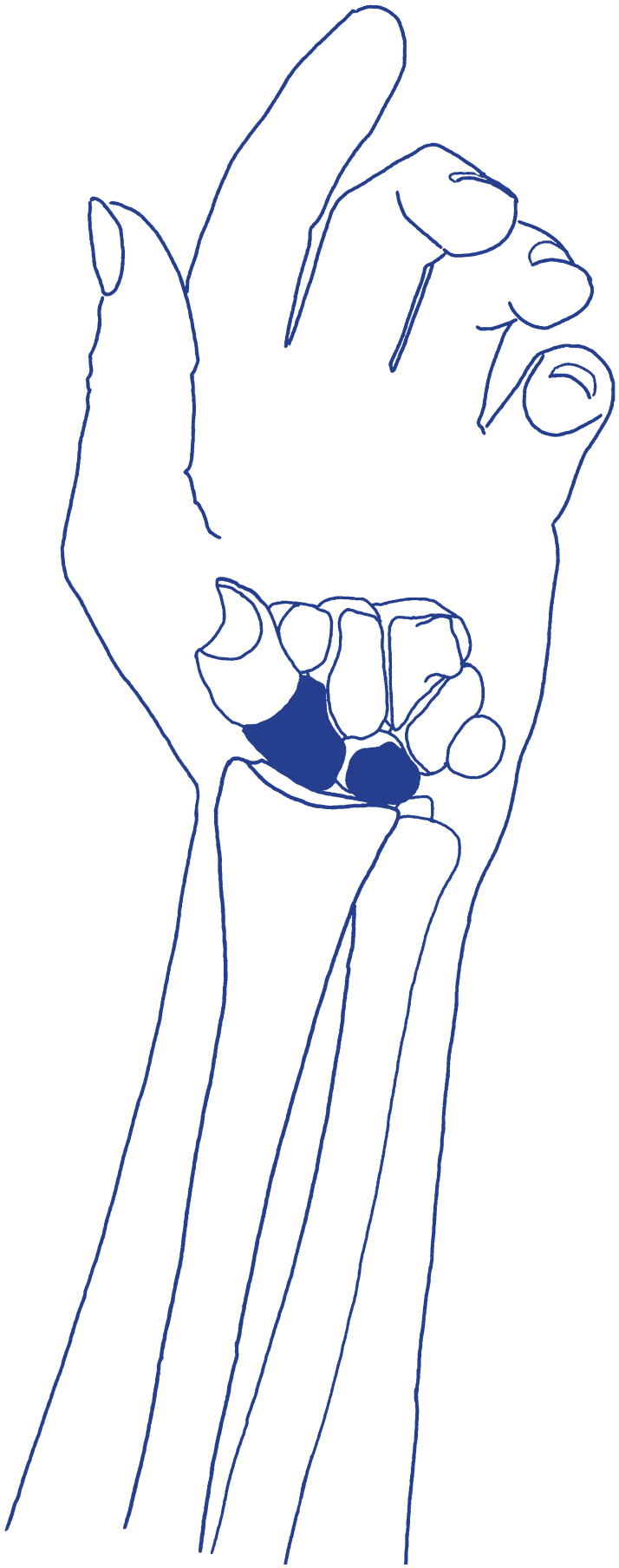
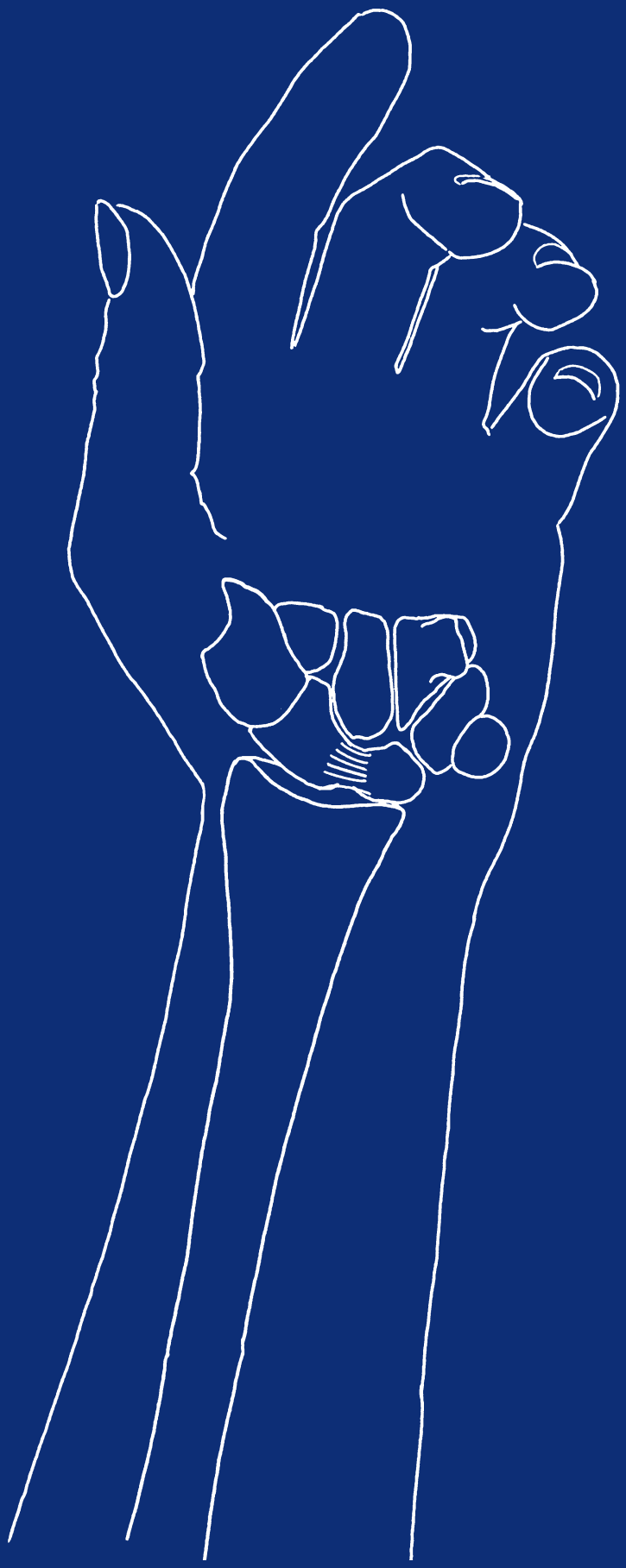


PART III

Ligamentous instability in the wrist: Scapholunate interosseous ligament injury



CHAPTER 9

The prevalence of scapholunate signal abnormalities on magnetic resonance imaging

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Hand (N Y). 2025 Sep 9:15589447251366675

ABSTRACT

Background

While trauma is a major cause of symptomatic scapholunate interosseous ligament (SLIL) pathology, many patients do not recall a specific injury or repetitive trauma. We report on 1) the prevalence of SLIL signal changes in patients who underwent wrist Magnetic Resonance Imaging (MRI) for various indications and 2) on the prevalence of SLIL signal changes on MRI in patients without prior wrist trauma.

Methods

This is a retrospective study evaluating 1021 patients who underwent wrist MRI or MR-Arthrogram. We collected data on SLIL signal changes on MRI. Patients were divided into six groups, based on age, to calculate the proportions of SLIL signal changes across different age groups.

Results

There was a total of 317 (31%) patients with SLIL signal changes, of whom, 264 (26% from 1021 and 83% from 317) had a documented low clinical suspicion of SLIL pathology. The prevalence was 15% amongst 18-30 year-olds, and increased to 50% in those over 70 year-old. Of the 317 patients with SLIL signal changes, 161 (51%) had no documented prior wrist trauma. The prevalence of SLIL signal changes in this group was 28% in 18–30 year-olds and increased to 80% in patients older than 70-years-old.

Conclusion

MRI signal changes demonstrating SLIL pathology in patients of a younger age may be more clinically meaningful since there is a lower prevalence of incidental SLIL pathology in these patients. Furthermore, it should be kept in mind that SLIL changes on MRI in older patients are common and may not represent acute pathology.

INTRODUCTION

Scapholunate interosseous ligament (SLIL) dissociation is the most common type of traumatic wrist instability (1–5) Magnetic resonance imaging (MRI) can detect signal changes in the SLIL associated with SLIL pathologies, such as degenerative changes, sprains, partial tears, or complete tears (6–8).

While trauma is one of the major causes of symptomatic SLIL pathology (2–4, 9–12) many patients do not recall a specific antecedent event or injury, nor any repetitive trauma that may have directly led to inury (1). However, changes in the SLIL may result from degeneration over time or may be associated with a multitude of conditions, such as osteoarthritis, infection, malignancy, and inflammatory arthropathies (13–15). As such, it is suspected that some of the SLIL changes seen on MRI may not result from a specific trauma.

The objective of this study was to report the prevalence of SLIL signal changes in patients who underwent wrist MRI for various indications, including traumatic and non-traumatic causes. Furthermore, we aimed to report the prevalence of SLIL signal changes on MRI in patients who do not report prior wrist trauma. Finally, we investigated the factors associated with SLIL signal changes in these two groups.

METHODS

Study design

The study has been approved by the Institutional Review Board (Mass General Brigham IRB) under protocol number 2019P000635, and uses a database spanning five academic hospitals. We requested all MRI reports of the wrist conducted between January 2018 and December 2020 through our Research Patient Data Registry (RPDR).

Data collection

Data were collected by two independent researchers. Any discrepancies in data collection were resolved by secondary review and consensus by the collectors. We included all wrist MRIs, of which 9% (n = 92) were MR Arthrograms. The MRI scanners used in this study were: 3T Siemens MAGNETOM Vida scanner®, 3T General Electric Premier scanner® and 1.5T Siemens MAGNETOM Avanto scanner®. Dedicated hand/wrist coils were used in all. All wrist MRIs were evaluated for SLIL signal changes by different musculoskeletal radiologists outside of the study team, including evaluation of volar, membranous, and dorsal components of the SLIL. The radiologists systematically reviewed the MRI/MR arthrogram, providing a comprehensive description of the SLIL ligament in the report. Intact SLIL in the MRI report was considered as no signal change. All other SLIL findings were denoted as signal change. Since SLIL signal changes were described with heterogeneity, it was not possible to differentiate between these options. Therefore, we chose to collect "SLIL signal changes" as a binary variable - being present or not present. If the patient previous had multiple wrist MRIs performed, we limited our analysis to the oldest report available. The second oldest report was used when the first MRI was aborted for technical reasons. Exclusion criteria included the following: 1. Patients under 18 years of age; 2. We excluded 22 patients due to missing data on clinical suspicion of wrist or hand pathology in both the clinical notes and MRI orders; 3. Prior SLIL, lunate, or scaphoid surgery; 4. Three patients with a malignant neoplasm located near the SLIL at the time the MRI was performed. The radiologist readers explicitly noted that the SLIL could not be assessed due to the presence of a tumor near the ligament. Pathology confirmed a malignant diagnosis in all 3 cases; and 5. MRIs exhibiting deficiencies, such as

incomplete sequencing, poor quality, or the presence of artifacts as described in the radiologist's report.

Demographic characteristics of the study cohort.

Demographic characteristics, including sex, race, age at the time of the MRI, and prior wrist trauma sustained by the wrist area due to external force or impact were retrospectively extracted from the medical record. Indications for MRIs were collected from physician orders (orthopaedic surgeons, plastic surgeons, hand surgeons, (orthopaedic) trauma surgeons, general practitioners, and internists) and relevant clinic notes that were directly related to the MRI request (Table 1). If suspicion for SLIL pathology was described in the clinical note or MRI order, the patient was classified as having "high clinical suspicion" for SLIL pathology. In cases where SLIL pathology was not listed in the physician's differential diagnosis, the patient was classified as having "low clinical suspicion". The indications for low clinical suspicion are listed in Table 1. We classified indications as low clinical suspicion when there was a specific non-SLIL diagnosis as the indication (ex. tumor or nerve pathology). Generalized wrist pain was also considered a non-specific diagnosis because the MRI was not specifically ordered with the suspicion that an SL injury was present. Missing data are reported in Table 1.

Statistical analysis

The normality of the data was assessed with a histogram and quantile-quantile plot. Since demographic descriptions were normally distributed, the data are presented with mean ± standard deviation (SD). Categorical data are presented with frequencies and percentages.

Patients were subdivided into six groups based on age: 1) 18 to 30 years (mean, 24 years; SD, 3 years), 2) 31 to 40 years (mean, 35 years; SD, 3 years), 3) 41 to 50 years (mean, 45 years; SD, 3 years), 4) 51 to 60 years (mean, 56 years; SD, 3 years), 5) 61 to 70 years (mean, 65 years; SD, 3 years), and 6) >71 years (mean, 77 years; SD, 4 years). Subsequently, we calculated the proportion of MRIs displaying signal changes in SLIL

in each subgroup categorized by high and low clinical suspicion. Furthermore, we calculated the proportion of MRIs showing SLIL signal changes in the non-prior wrist trauma group within each of the six age groups. We used the Locally Weighted Scatterplot Smoothing (LOWESS) (16) method to illustrate the frequency of SLIL signal changes in the overall population, high clinical suspicion, and low clinical suspicion groups, as it varies with age. A multivariate logistic regression model was used to analyze the association between the clinical indicators and SLIL signal changes in wrist MRIs in 1) All the patients and 2) In the nontraumatic wrist patients. A p-value of <0.05 was considered statistically significant. We used StataCorp. 2019. Stata Statistical Software: Release 16. College Station, TX: StataCorp LLC.

RESULTS

This study included 1021 patients with a mean age of 47±16 years, of which 47% (n = 476) were male and 79% were Caucasian (n = 778). In the included cohort, 46% (n = 468) had a prior wrist trauma. One hundred nine (11%) MRI scans were conducted for suspected SLIL pathology: high clinical suspicion. The most common reason for MRI requests with low clinical suspicion were the presence of ligamentous, tendinous, or muscular pathology (33%, n = 299), excluding SLIL pathology. The demographic data are presented in Table 1.

Table 1. Demographics

Variable	N (%)
Age (y), mean (±SD)	47 (16)
Male	476 (47)
Race*	
Caucasian	778 (79)
Black	98 (10)
Asian	50 (5)
Others	62 (6)
Prior wrist injury#	468 (46)
Indications	
High clinical suspicion for SLIL pathology	109 (11)
Low clinical suspicion for SILL pathology	912 (89)
General hand/wrist pain	121 (13)
Soft tissue/neoplasm	153 (17)
Bone pathology/fracture	196 (22)
Non SLIL ligament/tendon/muscle pathology	299 (33)
Infection/inflammation	113 (12)
Nerve pathology/impingement	30 (3)

y = years, SD = standard deviation, SLIL = scapholunate interosseous ligament; * missing = 33; # missing = 3

Among 1021 patient MRIs, 317 (31%) had SLIL signal changes. Of all the patients, 26% (264 out of 1021) of the patients had a low clinical suspicion of SLIL pathology and 5% (53 out of 1021) of the patients had a high clinical suspicion for SLIL pathology. In the

group with SLIL signal changes 83% (264 out of 317) of the patients had a low clinical suspicion of SLIL pathology and 17% (53 out of 317) of the patients had a high clinical suspicion for SLIL pathology. Exploring the MRIs showing SLIL signal changes (n = 317), we found that in the low clinical suspicion group, the prevalence of SLIL signal changes was 15% (32 out of 218) among patients aged 18-30 years and increased to 50% (41 out of 82) in patients older than 70 years (Table 2 and Figure 1). In the overall group, we found that 47% (53 out of 109) percent of the wrists indicated as a high clinical suspicion had SLIL signal changes on MRI, compared with 29% (264 out of 912) of the wrists that were indicated as low clinical suspicion (P< .001 by Fisher's exact test).

Table 2. Prevalence of SLIL Signal Changes in 1.021 Patients Who Underwent MRI of the Wrist

Variable	**Age Group (y)**						
	18-30	31-40	41-50	51-60	61-70	>70	Total
Wrist MRI (n)	218	207	164	212	138	82	1021
Proportion of MRIs showing SLIL signal changes, overall, % (n)	20 (43)	23 (47)	30 (50)	39 (82)	39 (54)	50 (41)	31 (317)
High clinical suspicion, %(n)	5 (11)	6 (12)	9 (14)	6 (12)	3 (4)	0 (0)	5 (53)
Low clinical suspicion, %(n)	15 (32)	17 (35)	22 (36)	33 (70)	36 (50)	50 (41)	26 (264)

y = years, SLIL = scapholunate interosseous ligament

Figure 1. Signal Changes and No Signal Changes in the SLIL on All Wrist MRI Scans (n = 1021)

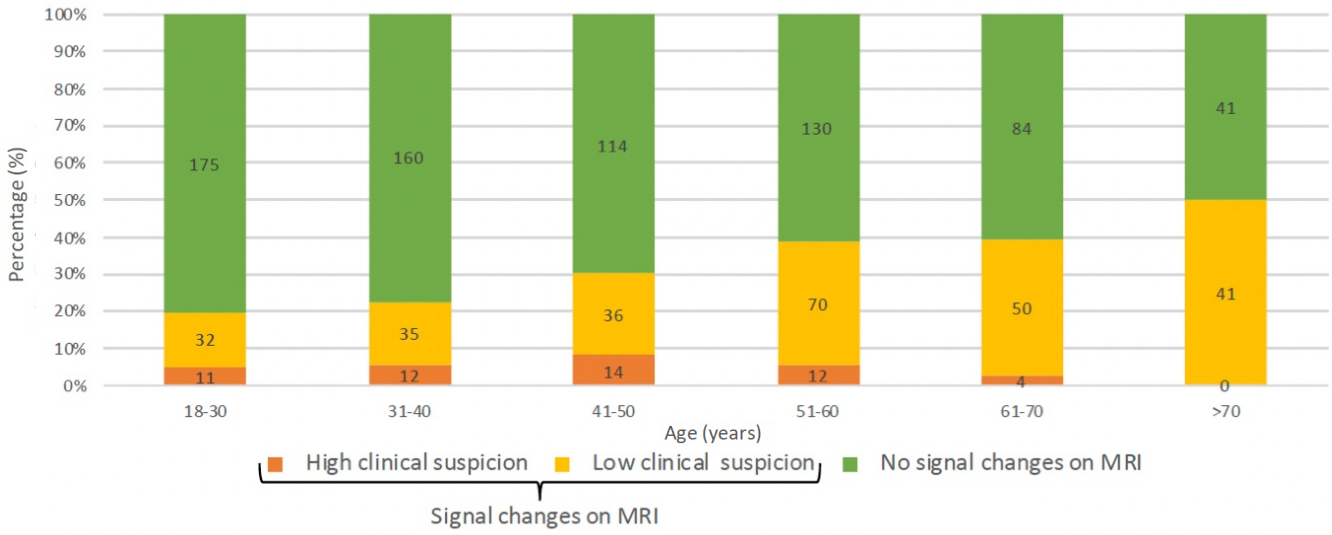
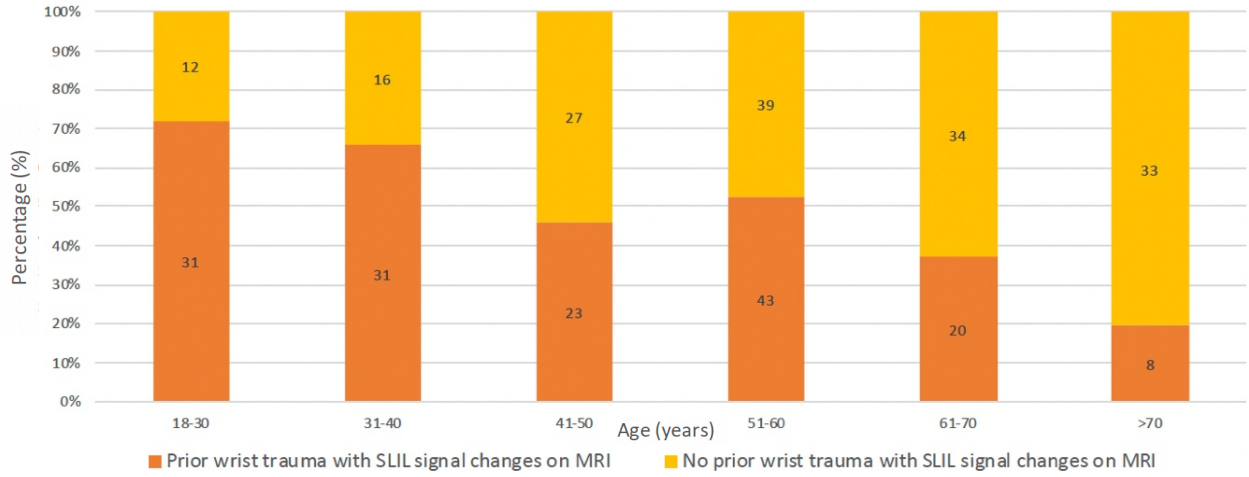


Figure 2. Prior and Non-prior Wrist Trauma in Comparison with MRI Scans that Show SLIL Signal Changes (n = 317)



Of all the MRIs with SLIL signal changes, 51% (161 out of 317) had no prior wrist trauma. In this group, the prevalence of SLIL signal changes was 28% (12 out of 43) in 18-30-year-olds and increased to 80% (33 out of 41) in patients older than 70 years (Figure 2).

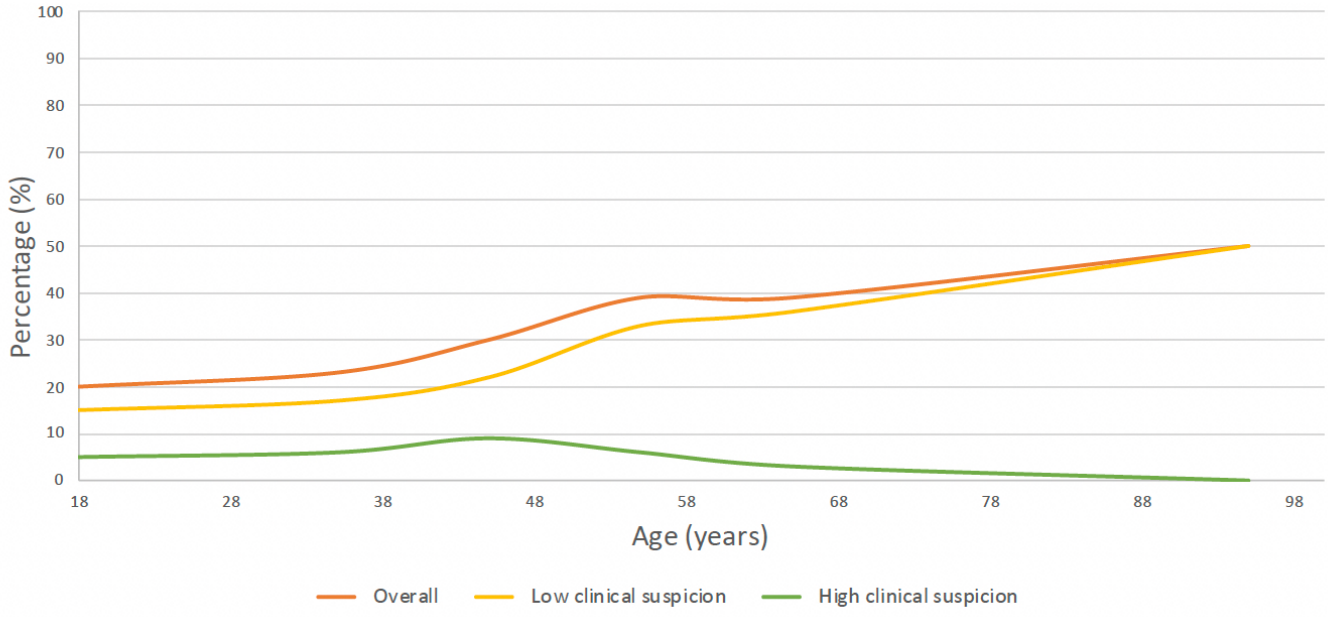
Multivariable logistic regression analyses showed that increasing age (Odds ratio [OR], 1.03 per year increase per age; 95% confidence interval [CI], 1.03-1.05; P< .001), male sex (OR, 1.46; 95% CI, 1.10-1.95; P= .009), and a high clinical suspicion for SLIL signal changes (OR, 3.59; 95% CI, 1.38-9.38; p= .009) were independent predictors for SLIL signal changes on MRI (Table 3). The LOWESS curve demonstrated a steadily increasing trend in SLIL signal changes on MRI correlated with age (Figure 3).

Table 3. Multivariable Logistic Regression Analysis of Factors Associated with SLIL Signal Changes on MRI (n = 986)

Variable	OR	Lower (95% CI)	Upper (95% CI)	SE	P-Value
Age	**1.03**	**1.03**	**1.05**	**0.00**	**<0.001**
Men	**1.46**	**1.10**	**1.95**	**0.21**	**0.009**
Race (reference: others)					
Caucasian	0.67	0.38	1.19	0.20	0.17
Black	0.91	0.45	1.83	0.32	0.79
Asian	0.84	0.36	1,96	0.36	0.69
Prior wrist injury	0,98	0.83	1.15	0.08	0.79
Indications					
High clinical suspicion for SLIL pathology	**3.59**	**1.38**	**9.38**	**1.76**	**0.009**
Low clinical suspicion for SLIL pathology (reference: nerve pathology/impingement)					
General hand/wrist pain	1.65	0.65	4.18	0.79	0.29
Soft tissue/neoplasm	0.91	0.36	2.3	0.43	0.84
Bone pathology/fracture	1.39	0.55	3.47	0.65	0.48
Non SLIL ligament/tendon/muscle pathology	1.08	0.44	2.64	0.49	0.87
Infection/inflammation	1.07	0.42	2.75	0.52	0.88

Bold indicated statistical significance ($p < .05$)
OR = odds ratio, CI = confidence interval, SE = standard error, SLIL = scapholunate interosseous ligament

Figure 3. A LOWESS Graph Depicts the Gradual Changes of Overall, High and Low Clinical Suspicion SLIL Signal Changes on MRI as it Varies with Age



In patients without prior wrist trauma, multivariable logistic regression showed that a higher age (OR, 1.04 per year increase in age; 95% CI, 1.03-1.06; P< .001) and a high clinical suspicion for SLIL signal changes (OR, 6.09; 95% CI, 1.59-23.28; P= .008) were independent predictors for SLIL signal changes on MRI (Table 4).

Table 4. Multivariable Logistic Regression Analysis of Factors Associated with SLIL Signal Changes on MRI in Non-trauma Patients (n = 536)

Variable	OR	Lower (95% CI)	Upper (95% CI)	SE	P-Value
Age	**1.04**	**1.03**	**1.06**	**0.01**	**<0.001**
Men	1.49	1.00	2.22	0.30	0.051
Race (reference: others)					
Caucasian	0.84	0.35	1.98	0.37	0.68
Black	1.09	0.38	3.15	0.59	0.88
Asian	0.45	0.12	1.68	0.30	0.24
Indications					
High clinical suspicion for SLIL pathology	**6.09**	**1.59**	**23.28**	**4.17**	**0.008**
Low clinical suspicion for SLIL pathology (reference: nerve pathology/impingement)					
General hand/wrist pain	2.57	0.81	8.18	1.52	0.11
Soft tissue/neoplasm	1.53	0.50	4.67	0.87	0.46
Bone pathology/fracture	3.07	0.94	10.04	1.86	0.06
Non SLIL ligament/tendon/muscle pathology	1.51	0.50	4.58	0.86	0.46
Infection/inflammation	1.55	0.51	4.73	0.88	0.44

Bold indicated statistical significance (p < .05)

OR = odds ratio, CI = confidence interval, SE = standard error, SLIL = scapholunate interosseous ligament

DISCUSSION

A total of 317 (31%) patients out of 1021 had SLIL signal changes, of whom 262 (26% from 1021 and 83% from 317) had low clinical suspicion of SLIL pathology prior to the MRI being obtained. In both the overall and the low clinical suspicion groups, the SLIL signal changes increased with age. In the full cohort, we observed that SLIL signal changes were associated with older age, male sex, and a documented high clinical suspicion. Furthermore, 161 of all patients with SLIL signal changes (51%) had no documented prior wrist injury. Also in this group the SLIL signal changes increased with age. Predictors for SLIL signal changes in this group were higher age and high clinical suspicion.

There are several limitations to this study. First, our data do not differentiate between different stages of SLIL pathology (e.g. degenerative change, sprains, partial tears, or complete tears).[6] Radiologists described SLIL signal changes in different ways (6). In many cases, it was not possible to discriminate between different verbal descriptions. Therefore, we chose to collect "SLIL signal changes" as a binary variable - being present or not present. In terms of this study, a binary treatment is reasonable to establish a Bayesian prior for interpretation of MRI/MR arthrogram; however, this data is not intended to describe partial versus complete SLIL injury.

Second, the presence of SLIL signal changes was determined by wrist MRI, but we did not examine the MRI images ourselves; we instead relied on radiology reports, intending to decrease bias.17 Furthermore, the images were reviewed by several musculoskeletal radiologists with varying levels of experience across five hospitals. The examination of SLIL signal changes may vary by radiologist and institution.

Third, there is no control for the type of exam or imaging parameters. There can be variation between MRI scanners (18), imaging techniques (19) and the use of gadolinium for MR arthrograms (20, 21). Anderson et al. and Potter et. al. described that MRIs with a higher resolution permitted more accurate depiction and localization of tears of the triangular fibrocartilage complex (22, 23). Furthermore, previous studies with different MRI scanners, using arthroscopy as a reference, described that the sensitivity MRI of the wrist to identify SLIL tears has been found to range between 46 and 63%, with specificity ranging between 86 and 91% (24,25). Regarding MR

arthrograms, Kader et al. described differences in sensitivity and specificity between MRIs and MR arthrograms for the detection of SLIL signal changes. The use of gadolinium in MRI showed a higher degree of sensitivity and specificity.24-Both MR and MR arthrograms were combined to reflect real-world clinical practice, where both imaging modalities are commonly used to evaluate SLIL pathology. Because the study is intended to establish a Bayesian prior for interpreting advanced imaging studies and considering the fact that the performance characteristics of MRI and MR arthrogram vary widely across studies, we chose not to treat these as separate groups.

Fourth, physicians with different specialties or subspecialties (orthopaedic surgeons, plastic surgeons, hand surgeons, (orthopaedic) trauma surgeons, general practitioners, internist) ordered the MRIs. The reason for patients' clinic visits sometimes focused on other possible wrist or hand pathologies. Overall, these results should be understood within a Bayesian statistical framework. Incidental SLIL signal changes are common and when identified on MRI in a low-probability setting, the SLIL finding rarely warrants treatment.

Fifth, we included a heterogeneous group of patients, which may have introduced variability in imaging types, diagnostic accuracy, and clinical coding. This heterogeneity can impact the internal validity of the findings. However, it also allowed for the inclusion of a larger and more representative cohort, thereby enhancing the generalizability of the results to broader clinical settings.

To our knowledge, there is a limited understanding of the prevalence of SLIL signal changes on radiological images. Based on radiographic gap views, Akahane et al. described that the incidence of asymptomatic scapholunate dissociation was significantly higher in patients over 30 years old than in those under 30 years old (26). Furthermore, studies have shown age-related changes to the carpal ligaments (27). These results were consistent with those in our study, which utilized MRI scans to show that, across our cohort, SLIL signal changes steadily increased with age. This trend was present both for patients with and without prior injury to the wrist. This suggests likely age-related and degenerative processes ongoing in the ligament, which can be visualized on MRI.

SLIL signal changes in patients with low clinical suspicion increased progressively with age. Among patients aged 18 to 30 years, 75% (15 of 20) showed SLIL signal changes, while in the >70 years age group, 100% (50 of 50) exhibited SLIL signal changes. Our overall data indicated that the majority of patients with SLIL signal changes had low clinical suspicion (84%).

Overall, this data suggests that there is a relatively high prevalence of patients with SLIL signal changes on MRI or MR Arthrogram who are asymptomatic. However, we found that less than half of the patients in the high suspicion group had an SLIL pathology detected on MRI. This could result from 2 possibilities: 1) Patients who had an actual SLIL injury were not identified by their imaging study or 2) Our ability to determine SLIL injury from clinical history and examination is quite imprecise. Most studies suggest that there is a meaningful false negative rate (28); however, it is also well established that the mechanism of SLIL injury overlaps with other wrist pathologies such as fracture or other sprains, and physical examination findings are relatively non-specific. Most likely, both of these factors account for this result.

Consequently, the pre-test suspicion of SLIL pathology is very important in determining whether an observed signal change on MRI is clinically meaningful. In other words, an MRI for the evaluation of SLIL signal changes in the wrist could be useful in patients of younger age with a s for clinical decision making. Similarly, in an older patient without a history of antecedent trauma, the presence of SLIL signal change may reflect expected degenerative change or other chronic pathology and may not warrant treatment.

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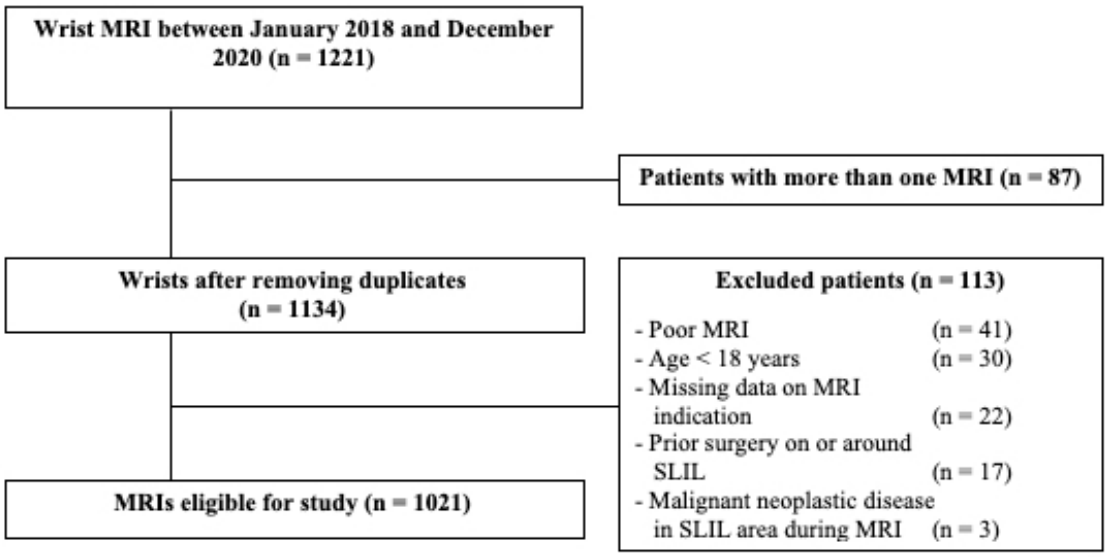
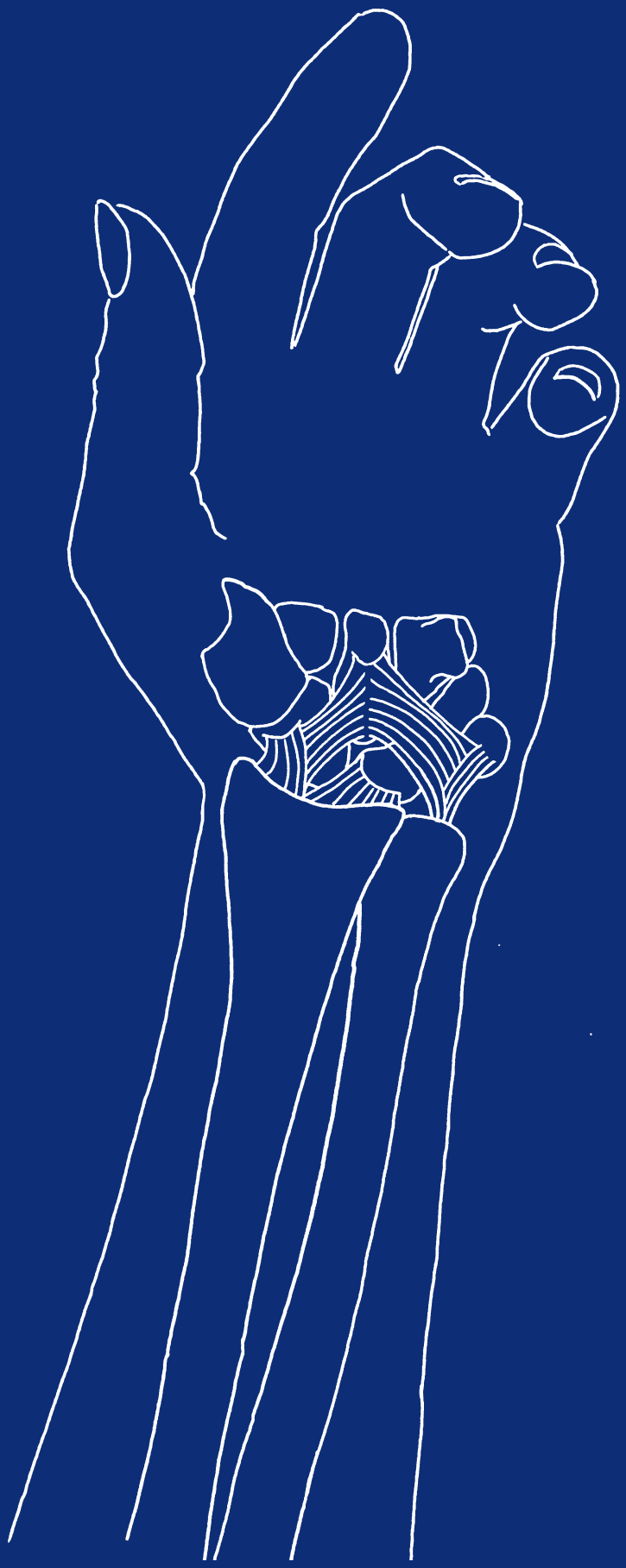
Appendix 1. Requested MRIs from the Research Patient Data Registry Between January 2018 and December 2020

Mri wrist arthrogram (left)
Mri wrist arthrogram (right)
Mri wrist joint with contrast (left)
Mri wrist joint with contrast (right)
Mri wrist joint without contrast (left)
Mri wrist joint without contrast (right)
Mri wrist joint (left)
Mri wrist joint (right)
Mri wrist joint with and without contrast (left)
Mri wrist joint with and without contrast (right)
Mri wrist with contrast (left)
Mri wrist with contrast (right)
Mri wrist without contrast (left)
Mri wrist without contrast (right)
Mri wrist (left)
Mri wrist (right)
Mri wrist with and without contrast (left)
Mri wrist with and without contrast (right)
Mri wrist joint (left)
Mri wrist joint (right)
Mri wrist (left)
Mri wrist (right)
Mri wrist w contrast
Mri wrist w/o con
Mri wrist w & w/0 con
Mri wrist w/o con
Mri wrist w & w/0 con
Mri wrist w contrast
Mri wrist w/o con

Appendix 2. Patient flowchart based on inclusion and exclusion criteria





CHAPTER 10

Association of extrinsic ligament injury with diastasis in scapholunate ligament injury

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ABSTRACT

Purpose

Extrinsic ligament injury is necessary for scapholunate (SL) diastasis to occur in SL ligament injury. Prior studies demonstrate an association between dorsal extrinsic ligament injury and SL diastasis, but it is unclear what is the importance of volar extrinsic injury. This study aimed to characterize injury to the Dorsal Intercarpal Ligament (DIC), Dorsal Radicarpal Ligament (DRC), Volar Extrinsic Ligaments (LRL/SRL/RSC) and Scaphotrapezotrapezial (STT) ligaments to determine what extrinsic ligament injuries are independently associated with SL diastasis.

Methods

We conducted a retrospective cohort at a multicenter academic institution and identified 101 patients with MRI-confirmed SL ligament injuries from 2018 to 2023. Three musculoskeletal radiologists independently assessed the MRIs for the presence of SL ligament injuries, volar extrinsic ligament (LRL/SRL/RSC), STT ligament and dorsal extrinsic ligament (DIC and DRC) injuries and quantified SL diastasis.

Results

In patients with SL diastasis > 2mm, injuries to the volar extrinsic ligaments (LRL/SRL/RSC) were found in 42% of cases, compared to 11% in those without SL diastasis. Dorsal extrinsic injuries (DIC and/or DRC) were more frequently observed in cases with SL diastasis (60%) than in those without SL diastasis (25%). Injury to the volar extrinsic ligaments and any of the dorsal extrinsic ligaments (DIC and/or DRC) was significantly associated with SL diastasis (OR 4.44, 95% CI [1.51–14.27], and 3.39, 95% CI [1.33 – 8.93], respectively, $p<0.05$). The inter-observer agreement showed fair to moderate agreement on injured ligaments and substantial for uninjured extrinsic ligaments.

Conclusion

This study demonstrates that in patients with MRI-confirmed SL diastasis, injury to eighter the volar extrinsic ligaments or the dorsal extrinsic ligament injuries are each

independently associated with SL diastasis > 2mm. This is an important new concept that volar extrinsic ligament insufficiency alone is meaningful in scapholunate instability and may influence reconstruction strategies based on the specific ligamentous structures involved.

INTRODUCTION

Scapholunate (SL) diastasis occurs when the scapholunate ligament and other extrinsic ligaments of the wrist are injured. Short et al. demonstrated that the sectioning of extrinsic ligaments and the order of sectioning is important in the development of kinematic wrist pathology (1). Lee et al. demonstrated that in a cadaveric model, arthroscopic sectioning of the scapholunate ligament alone was not sufficient to result in Geissler grade IV SL instability (2). As the radioscaphocapitate (RSC) and long radiolunate (LRL) ligaments were sectioned, the wrists demonstrated Grade III instability. Grade IV instability only occurred after sectioning of the dorsal radiocarpal ligament (DRC) and dorsal intercarpal ligament (DIC) (2).

In vivo studies are also consistent with these cadaveric studies: In an analysis of MRIs of 90 patients with SL injuries, Özkan found that injury of DIC and/ or DRC was associated with scapholunate diastasis greater than 2 mm (3). However, in this cohort, only 58% of patients with SL diastasis greater than 2 mm had injury of the DIC and/or DRC, suggesting that other extrinsic ligament injury patterns may also lead to SL widening. In the study by Lee et al., the extrinsic ligament sectioning followed a distinct order, starting with the SL ligament, then the volar extrinsic ligament, and finally the dorsal extrinsic ligaments. Once the dorsal extrinsics were sectioned, Geissler Grade IV diastasis was observed arthroscopically; however, it is uncertain how a different order of sectioning would affect results (2). It is unclear to what degree to which the dorsal extrinsic ligaments and the volar extrinsic ligaments independently contribute to stability when the SL ligament is injured. Understanding whether injury to the DIC, DRC, or the volar extrinsic ligament complex is associated with scapholunate diastasis may help explain the variation in outcomes of different reconstruction options, such as dorsal capsular advancements or FCR ligament reconstructions.

Therefore, this study aimed to: 1) characterize dorsal or volar extrinsic ligament injury on MRI of patients with a known SL ligament injury and 2) analyze whether specific extrinsic ligament injury was independently associated with SL diastasis greater than 2mm.

METHODS

Study design and data collection

Our Institutional Review Board approved this retrospective study. The institutional database of a healthcare system in the Northeastern United States, comprising five hospitals, was searched between January 2018 and December 2021 for ICD-10 codes that may represent an SL injury (Supplement Table 1). Those records were manually screened for an MRI or MR arthrogram reports indicating injury to the SL ligament. The exclusion criteria were: 1) age < 18 years; 2) absence of a clinical history of trauma; 3) concomitant fracture; 4) scaphoid lunate advanced collapse (SLAC); 5) inflammatory arthritis; 6) previous ipsilateral wrist fracture; 7) irretrievable or suboptimal MRI and 8) avascular necrosis scaphoid or lunate (Figure 1). After exclusions, the total cohort consisted of 101 patients.

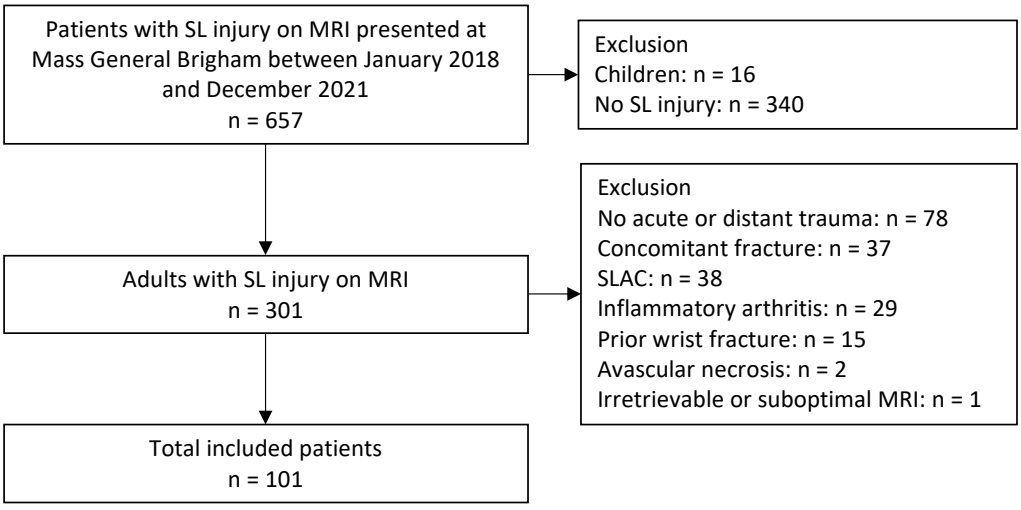
Three attending fellowship-trained musculoskeletal radiologists independently reviewed and scored the MRI scans on a picture archiving and communications system and evaluated the wrist for SL widening (mm). SL injury was characterized as a full-thickness tear or partial tear/ sprain. SL distance of 2 mm or more and SLIL injury was considered as was considered evidence of static SL diastasis, as an SL interval >2 mm has been widely used to distinguish normal from pathologic widening and to define static scapholunate instability in prior literature (4). Among the 21 patients who underwent arthroscopy, all had findings consistent with SL ligament injury.

They also reached a consensus on the integrity of the SLIL, volar extrinsic ligaments long radio lunate (LRL), short radio lunate (SRL), or radioscaphocapitate ligaments, scaphotrapeziotrapezoid (STT) ligament, DIC and DRC ligament, defined as "normal" or "injured". We combined the LRL, SRL, and RSC ligaments into a single group (“volar extrinsic ligaments”), as these ligaments function as an interrelated stabilizing complex on the volar side of the wrist and are difficult to reliably differentiate as isolated injuries on MRI, making separate analysis unlikely to yield clinically meaningful distinctions. The final determination of injury was based on agreement of 2 or more readers. Type 2 lunates (defined as the presence of a distal hamate facet) were not excluded from analysis. The presence of a type 2 lunate was recorded and evaluated in a secondary subgroup analysis.

Statistical analysis

The normality of the data was assessed with a Shapiro-Wilk test. Normally distributed data was presented as means and standard deviation (±SD), non-parametric data as medians and interquartile ranges (IQR) and categorical data with frequencies and percentages. A Wilcoxon Rank Sum test was performed to assess the association between age and static SL diastasis for non-parametric data. Fisher's Exact Test was used to analyze the association between static SL diastasis (SL interval > 2 mm) and sex or hand dominance. Univariable and multivariable logistic regression analyses assessed the association between SL diastasis (>2 mm), age, and injuries to four ligaments (LRL/SRL/RSC, STT, DIC, and DRC) with odds ratios (ORs) adjusted for age, sex and the presence of other ligament injuries. We conducted separate multivariable logistic regressions for injuries to the extrinsic ligaments, adjusting for age and sex. Additionally, the variance inflation factor (VIF) was calculated for all multivariable regression models to assess multicollinearity. The Interclass correlation coefficient (ICC) and the 95% confidence intervals (95% CI) were calculated based on absolute agreement and a two-way mixed-effects model for the agreement on SL interval measurements. The Fleiss' Kappa for inter-observer reliability was calculated, as well as the agreement on individual categories ("Injured" and "Not injured"). We adhered to the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) guidelines (5).

Figure 1. Flowchart of the study population; SL: Scapholunate; SLAC: scaphoid lunate advanced collapse



RESULTS

Patient characteristics and injury to the extrinsic or intrinsic ligaments

One hundred and one patients with SL injury were included; of those, 40 (40%) patients had an SL gap of > 2 mm. SL diastasis occurred in 77% (31/40) of male patients versus 23% (9/40) of female patients ($p<0.05$) (Table 1). We found that the mean SL angle was 57 degrees (SD 14.2), and the mean radiolunate (RL) angle was 3.5 degrees (SD 13.8). Twenty-five patients (25%) had a type 2 lunate. No significant difference in SL gap was observed between type 1 and type 2 lunates (median 1.72 mm vs 1.87 mm; $p = 0.84$).

Table 1. Patient Characteristics

		Static SL diastasis	
Variables	**All patients (n = 101)**	**No (n = 61)**	**Yes (n = 40)**
Age at time of MRI, y (median ([IQR])	46 [35-58]	43 [33-56]	48.5 [36.8-60.3]
Sex			
Female	40 (39.6)	31 (51)	9 (23)
Male	61 (60.4)	30 (49)	31 (77)
Field strength of MRI			
Tesla 1.5	34 (33.6)	18 (29)	16 (40)
Tesla 3	63 (62.3)	42 (69)	21 (53)
Dominant side involved, n (%)	55 (54.4)	30 (49)	25 (63)
SL gap, mm (median [IQR])	1.73 [1.3-2.6]	1.43 [1.2-1.7]	2.90 [2.4-3.9]

Value is displayed as median with interquartile range for continuous non-parametric variables, as mean with standard deviation for continuous variables with normal distribution, and as number with percentage for categorical variables. SL diastasis is defined as an SL dissociation of ≥ 2 mm.

Injury to the volar extrinsic ligaments (LRL/SRL/RSC) was more frequent in patients with SL diastasis than without SL diastasis, 42% (17/40) versus 11% (7/61), respectively ($p<0.05$). Injury to the STT ligament occurred in 38% (15/40) with SL diastasis and in 21% (13/61) without diastasis ($p=0.11$). Patients with SL diastasis had injury to the DIC ligament compared to patients without SL diastasis, (40%, 16/40) v. 20%, (12/61), $p<0.05$). Similarly, patients with SL diastasis had injury to the DRC ligament more frequently than those without diastasis (32%, (13/40) v. 15%,(9/61),

p <0.05) (Table 2). In 5 cases, both the volar extrinsics and dorsal extrinsics were injured, of which all had SL diastasis.

Table 2. Extrinsic ligament injury and SL diastasis on MRI

		Static SL diastasis		
Variables	**All patients (n = 101)**	**No (n = 61)**	**Yes (n = 40)**	**p-value**
LRL/SRL/RSC injury on MRI, n (%)				**<0.05**
Normal	77 (76.3)	54 (89)	23 (58)	
Injured	24 (23.7)	7 (11)	17 (42)	
STT ligament injury on MRI, n (%)				0.11
Normal	73 (72.1)	48 (79)	25 (62)	
Injured	27 (27.9)	13 (21)	15 (38)	
DIC ligament injury on MRI, n (%)*				**0.04**
Normal	72 (71.3)	48 (79)	24 (60)	
Injured	28 (27.7)	12 (20)	16 (40)	
DRC ligament injury on MRI, n (%)*				**0.05**
Normal	76 (75.2)	49 (80)	27 (68)	
Injured	22 (21.7)	9 (15)	13 (32)	
LRL/SRL/RSC and STT ligament injury on MRI, n (%)				**<0.05**
Normal	59 (58.4)	44 (72)	15 (38)	
Injured	42 (41.6)	17 (28)	25 (62)	
Dorsal extrinsic ligament (DIC/DRC) injury on MRI, n (%)				**<0.05**
Normal	60 (59.4)	46 (75)	16 (40)	
Injured	39 (38.6)	15 (25)	24 (60)	
Any ligament injury (LRL/SRL/RSC, STT, DIC, DRC), n (%)				**<0.05**
Normal	43 (42.6)	38 (62)	5 (13)	
Injured	58 (57.4)	23 (38)	35 (87)	

Value is displayed as median with interquartile range for continuous non-parametric variables, as mean with standard deviation for continuous variables with normal distribution, and as number with percentage for categorical variables. Fisher' exact test. *In one patient the DIC was not assessable; In three patients the DRC was not assessable. Bold indicates significance, p<0.05.

Association between SL diastasis and concomitant ligament injury

The univariate analysis revealed that male patients and those with injury to the volar extrinsic ligaments, the DIC ligament, and the DRC ligament were associated with the occurrence of SL diastasis (Table 3).

Table 3. Univariable logistic regression analysis of factors associated with the presence of SL diastasis

Variables	OR	95% CI	P-value
Age at time of MRI	1.02	0.99 - 1.05	0.06
Sex (Male)	0.28	0.11 - 0.66	**<0.05**
Field strength (3.0 Tesla)	0.56	0.24 - 1.32	0.19
Dominant side involved	1.41	0.62 - 3.23	0.40
LRL/SRL/RSC injury	5.70	2.16 - 16.5	**<0.05**
STT ligament injury	2.21	0.91 - 5.44	0.08
DIC ligament injury	2.67	1.10 - 6.64	**<0.05**
DRC ligament injury	2.62	1.00 - 7.12	**0.05**

OR: Odds Ratio, 95% CI: 95% Confidence Intervals. Bold indicates significance, p<0.05.

A multivariable analysis of the volar extrinsic ligaments (LRL/SRL/RSC) and combining injuries to the dorsal extrinsic ligaments (DIC and/or DRC), adjusted for age and sex, demonstrated that injury to either the volar (LRL/SRL/RSC) and dorsal (DIC and/or DRC) extrinsic ligaments were independently associated with the presence of scapholunate (SL) diastasis (OR 4.44, 95% CI [1.51–14.27], p < 0.05 and OR 3.39, 95% CI [1.33 – 8.93], p < 0.05, respectively). All variance VIF values were close to 1.0, indicating no multicollinearity between variables. (Table 4). All variance VIF values were close to 1.0, indicating no multicollinearity between variables. (Table 4).

Table 4. Multivariable logistic regression for LRL/SRL/RSC and DIC and/or DRC ligament injury associated with SL-diastasis, adjusted for age and sex

Variables	OR	95% CI	P Value	VIF
Age	1.02	0.99 - 1.05	0.18	1.01
Male sex	0.4	0.14 - 1.05	0.06	1.01
LRL/SRL/RSC injury	4.44	1.51 - 14.27	**0.03**	1.01
Dorsal extrinsic ligament (DIC and/or DRC) injury	3.39	1.33 - 8.93	**0.02**	1.02

OR: Odds Ratio. 95% CI: 95% Confidence Intervals. VIF: Variance Inflation Facto. Bold indicates significance, p<0.05.

Inter-Observer Agreement

Measurement of the SL distance by the three fellowship-trained musculoskeletal radiologists demonstrated excellent reliability (ICC = 0.93, 95% CI 0.89 –0.95). The inter-observer reliability among radiologists evaluating ligament injury was fair for the evaluation of volar extrinsic ligaments (κ = 0.39) and moderate for the STT, DIC, and DRC ligaments (κ = 0.41, 0.48, and 0.43, respectively).

DISCUSSION

In this study, three fellowship-trained radiologists analyzed 101 MRIs of patients with scapholunate ligament injury and found that scapholunate diastasis > 2mm was independently associated with either injury to the volar extrinsic ligaments (LRL/SRL/RSC) or the dorsal extrinsic ligaments (DIC and/or DRC).

Prior biomechanical studies emphasize that SL diastasis requires injury to the SL ligament, as well as to secondary stabilizers. Short et al. demonstrated that serial sectioning of the SL, STT, RSC, DIC, and DRC ligaments led to kinematic changes in the wrist, and which ligaments and what order they were sectioned was important (1). Furthermore, Pérez et al. found that sectioning of the STT ligaments led to the greatest increase in radio lunate angle (DISI deformity) (6), consistent with the original ideas of Drewniany et al. that the STT ligament is a critical stabilizer of the wrist (7). Prior work suggests that STT ligament injury has an association with radio lunate angle changes/ sagittal plane lunate rotation. Sectioning of other extrinsic ligaments in vitro with an intact STT result in scapholunate interval widening, which may explain the lack of association of STT injury with scapholunate diastasis observed in the present study (6, 8).

In the present cohort, dorsal subluxation of the scaphoid was uncommon. Among the 28 patients with STT ligament injury, only two demonstrated dorsal scaphoid subluxation. Overall, dorsal subluxation was observed in 10 patients across the entire cohort. This suggests that although prior biomechanical studies highlight the role of the STT ligament in sagittal plane stability and lunate rotation, STT injury on MRI does not necessarily translate into overt radiographic scaphoid malalignment. These findings support the concept that SL diastasis may occur in the absence of gross sagittal plane instability and further emphasize the multifactorial nature of carpal stability.

Retrospective in vivo MRI studies support these biomechanical data (9, 10). Adler et al. found that in 8 patients with SL diastasis, all demonstrated injury to the RSC and 5 had injury to the dorsal extrinsics (11). Özkan et al. found that dorsal extrinsic ligament injury was significantly associated with SL diastasis in the analysis of MRIs from 90 patients (3). Our study further confirmed that dorsal extrinsic

ligament injury is independently associated with SL diastasis but also demonstrated that volar extrinsic ligament injury has an independent association with diastasis, suggesting that different patterns of extrinsic ligament injury exist in SL diastasis.

If there are different patterns of extrinsic ligament injury in SL diastasis, this may explain in some part the heterogeneity of outcomes of SL reconstruction. In patients with dorsal extrinsic ligament injury, reconstruction methods that rely on the integrity of the dorsal extrinsic ligaments may not be as successful. For example, if the dorsal radiotriquetral ligament is injured, a tri-ligament tenodesis may be less preferred. Conversely, identification of volar extrinsic ligament injury on preoperative MRI may support consideration of reconstruction techniques that directly address volar stabilizers, such as ANAFAB or other volar-based reconstructions. In this context, MRI assessment of extrinsic ligament involvement could improve intervention by tailoring reconstruction to the predominant ligament injury pattern. Further studies may help determine if MRI findings may be useful in selecting a surgical technique.

These findings should be interpreted in the context of the study's limitations. First, this was a retrospective study, which limits causal inference. Case identification was based on ICD-10 diagnostic codes, which, although pragmatic and commonly used, may be subject to coding inaccuracies or misclassification and could introduce selection bias. However, all included patients had MRI-confirmed scapholunate ligament injury, which likely mitigated the risk of significant misclassification.

Second, ligament injury was assessed using MRI alone, without arthroscopic or intraoperative correlation, which may have affected the accuracy of ligament injury classification. Additionally, both 3-Tesla and 1.5-Tesla MRI scanners were used, and 18% of patients underwent MR arthrography rather than conventional MRI. We did not perform formal subgroup analyses according to field strength or arthrography status because the subgroup sizes were too small to permit meaningful comparisons. Although higher field strength may plausibly improve visualization of volar extrinsic ligaments and diagnostic reliability, which warrants further investigation. While this imaging heterogeneity may influence ligament visualization, it also reflects routine clinical practice and improves generalizability.

Third, we used a binary classification of "injured" versus "uninjured". It is common to use terminology such as "partial tear" or "sprain" to indicate partial injury of the ligament. Despite this common descriptor, in designing the study, we deliberately chose a binary classification to commit readers to determine if a injury is meaningful and also to simplify statistical handling of the data. Fourth, although reading of most extrinsic ligament injury had moderate agreement, the agreement for volar ligament injury was fair among the three readers. This likely reflects the inherent difficulty of assessing these structures on MRI. The volar extrinsic ligaments are thin, obliquely oriented, and closely apposed to capsular structures and tendons, which can make partial injury difficult to distinguish from normal anatomic variation, particularly on routine clinical MRI sequences. The use of majority consensus among the three readers helps mitigate this limitation. Furthermore, radiologists were not blinded and were aware of the study's aims, which may have introduced some bias during the reading of the MRI scans. Finally, the relatively small sample size and event frequency likely contributed to the wide confidence intervals observed in the multivariable analyses, limiting precision and potentially inflating effect estimates. Future studies with larger sample sizes may allow analysis of scapholunate widening as a continuous measure to further elucidate relationships between the extent of ligament injury and the degree of diastasis.

In conclusion, we found that diastasis >2mm in the setting of scapholunate ligament injury is independently associated with volar extrinsic ligament injury or dorsal extrinsic ligament injury. This finding suggests that there may be different patterns of extrinsic ligament injury that may have bearing on which injuries may be successfully treated non-operatively or selection of operative technique.

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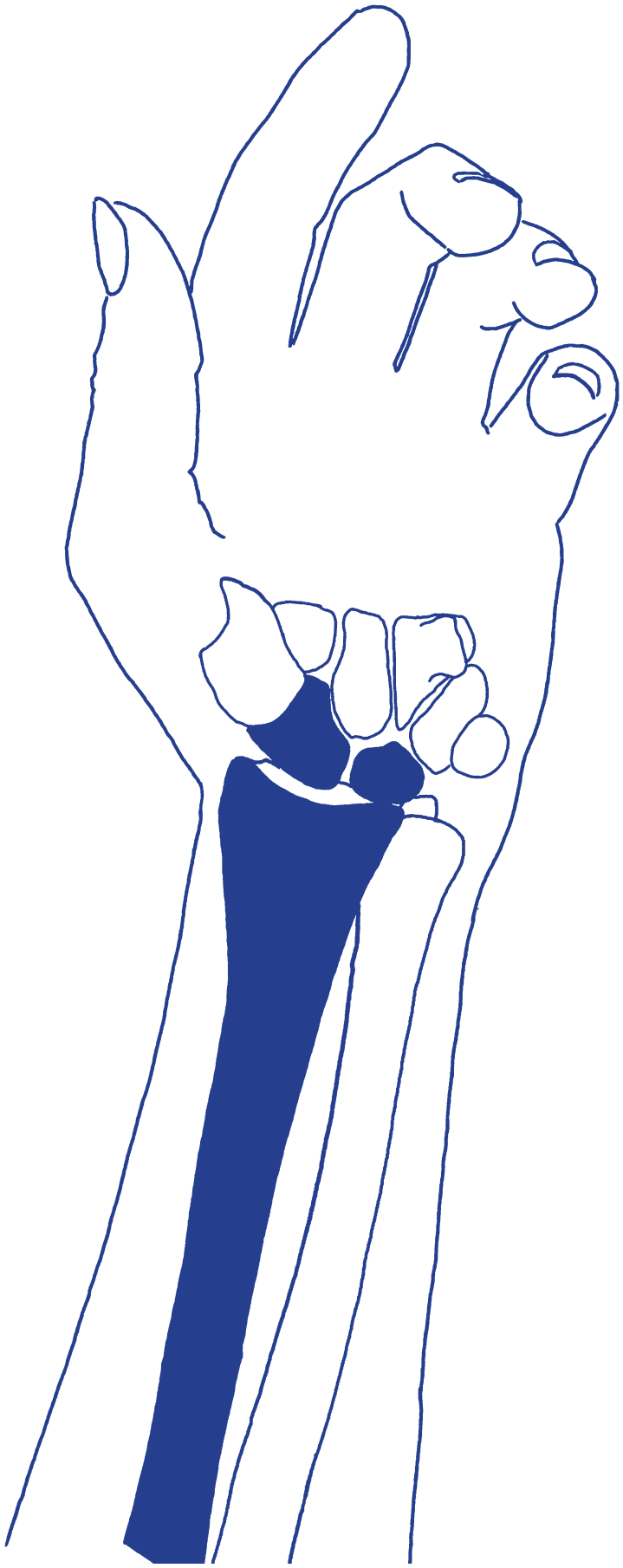
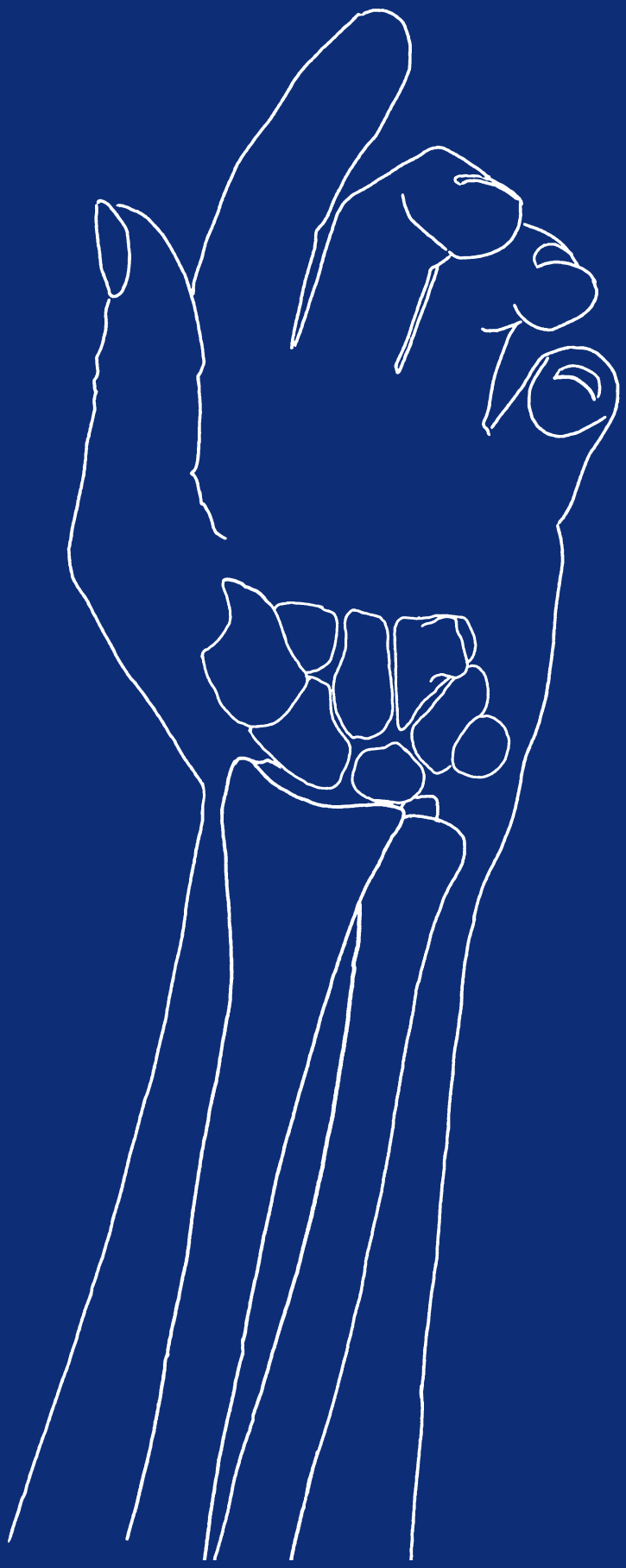


PART IV

General discussion, future perspectives, and summary



CHAPTER 11

General discussion and future perspectives

GENERAL DISCUSSION AND FUTURE PERSPECTIVES

A fall onto outstretched hand (FOOSH) might result in either a DRF or a difficult to detect scapholunate interosseous ligament (SLIL) injury. While reduced DRFs can be unstable resulting in secondary displacement, the SLIL ligament injury causes instability in between the carpal bones. This thesis aims to enhance diagnostic accuracy, minimize variability in treatment strategies of both primary pathology as complications, and establish a foundation for more personalized and effective management of the broad scope of both osseous and ligamentous wrist instability.

OSSEOUS INSTABILITY IN THE WRIST - DISTAL RADIUS FRACTURE

Diagnosing and predicting DRFs' instability remains a crucial challenge and a subject of debate in clinical practice. Part I of this thesis addressed key questions regarding the optimal diagnostic approach, classification of fractures, prediction of loss of threshold alignment, and the potential role of Artificial Intelligence (AI) regarding these questions.

Can DRF instability be diagnosed and even predicted by the surgeon?

To address the ability of surgeons to predict instability, it is essential to evaluate the imaging modalities on which such predictions can be based. As prior, low-grade evidence suggested that CT imaging is more reliable than conventional radiography for assessing intra-articular fractures, this thesis (**Chapter 2**) reinforces that CT imaging provides a superior evaluation of critical parameters, particularly intra-articular step-off and gap, and radiographs tend to underestimate fracture displacement compared to CT scans (1-5). CT offers improved interobserver reliability and enhanced surgical decision-making. Given these advantages, a more liberal approach to CT imaging should be considered in cases of suspected intra-articular involvement in patient fit for surgery. This can facilitate early surgical planning, reduce the need for repeated imaging, and enhance the visualization of key anatomical structures, like the radiocarpal joint and the distal radioulnar joint. Additionally, dorsal and volar comminution, ulnar variance, and angulation, often underestimated on radiographs compared to CT imaging, are known predictors of secondary

displacement (6-11). Still, routine CT for all DRFs may be impractical due to cost, radiation exposure, and limited availability. A selective approach, focusing on younger patients, active older individuals, fractures at higher risk of instability, and cases with uncertain operative indications, can balance practicality with benefit. Furthermore, patient factors such as female sex and advanced age (**Chapter 4 & 5**), which increase the risk of losing acceptable alignment, should guide post-reduction CT imaging use.

Beyond imaging modalities themselves, emerging AI applications can further enhance diagnostic accuracy. An overview of the literature in **Chapter 3** suggests that AI used to detect and classify DRFs applied on conventional radiographs can perform comparable to human observers, showing promising performance for diagnostic accuracy.

Combining the findings of these chapters suggest that, particularly in cases where subtle fracture lines might be missed on radiographs, the role of AI analyzing on additional CT can be beneficial. Data on the use of AI specifically for DRFs on CT images are still evolving. A study by Dankelman et al. (2023), not included in this thesis, demonstrated benefits of AI-assisted detection and classification on CT for other fractures, but strong evidence for DRFs in particular remains scarce (12). Parallel to the growth of AI applications, 3D visualization of DRFs from CT scans is increasingly used for surgical planning and can potentially lower complication rates (13-16). While 3D visualization of DRFs lies outside the scope of this thesis, it remains a promising avenue for achieving a more precise evaluation of complex fractures, with or without AI.

Even with improved diagnostic and classification tools, whether based on radiographs, CT imaging, or AI analyzed, the question remains how effectively one can predict the stability or instability of reduced DRFs. Traditional predictive methods, such as McQueen's equations and Lafontaine's criteria, are widely cited but have shown variable outcomes (8, 17). **Chapter 3** did not identify any evidence regarding AI's ability to anticipate loss of alignment thresholds on radiographs. Before AI can be incorporated into predictive workflows, it is essential to establish how reliable

surgeons can predict instability. Overall, the findings in **Chapter 4 & 5** revealed that surgeons demonstrate limited accuracy in predicting fracture displacement, with 55% using radiographs and 70% using CT. These findings highlight a major opportunity for AI but also underscore the challenge of predicting a dynamic process from static images. An analogy is that of a single photograph of a car: one cannot definitively determine whether the car is moving or stationary, based on a lone static image. Similarly, static radiographs or CT scans may not fully capture the complex biomechanical forces that drive fracture displacement. Consequently, while imaging can play a role in making more accurate predictions, additional factors contributing to fracture movement must also be considered.

Where do we stand now?

Optimizing DRF management requires imaging (radiographs and in some cases also CT), patient-specific considerations, and improvement of prediction of secondary displacement by predictive methods, potentially aided by AI applications. While AI can improve diagnostic accuracy, current models overlook factors like comorbidities, patient preferences, and treatment goals. A more proactive approach can involve earlier and more definitive assessment of fracture alignment, particularly through CT rather than plain radiographs. Additionally, considering female sex and advanced age as predictive factors for secondary displacement can help determine more accurately whether surgical intervention is warranted before the fracture shifts. This thesis helps to construct a predictive and treatment model incorporating imaging, AI applications, and patient-specific factors.

What are we aiming for in the future?

The direct impact of CT findings on the choice of surgical intervention and eventually on the outcomes remains underexplored. Future prospective research should assess whether earlier or more frequent CT use, particularly in borderline cases, can meaningfully influence treatment indications or improve patient-reported outcomes. This is especially relevant in diverse patient groups, with variance in activity levels, including those over the age of 65, where previous studies have shown no clear

association between malunion and functional outcomes (18, 19). However, as life expectancy rises and older adults remain more active, treatment decisions should be based more on functional status than chronological age. In fit and active older individuals, a more proactive or even aggressive treatment strategy may still be warranted, despite their age. This shift presents a potential direction for future research.

Furthermore, cost-benefit analyses of routine CT use are needed, considering clinical benefit, radiation exposure, and actual financial costs. In parallel, the integration of AI applications offers promising potential. Externally validated models that combine imaging with patient-specific data (e.g., comorbidities, function, preferences) can enhance diagnostic accuracy and reduce variability in treatment decisions. As demonstrated in this thesis, AI has already shown potential in the classification and detection of DRFs on radiographs. However, predicting fracture instability, and helpful in the counseling for surgical intervention, remains a significant challenge and an area for future investigation. A recent study has shown that incorporating AI and combined imaging and clinical data can improve treatment decision accuracy (20).

Future research should further explore the potential role of AI in improving the estimation of instability of DRFs. Until then, clinical judgment guided by imaging and patient context remains essential. Developing integrated, predictive tools, combining imaging, AI applications, and patient-specific clinical data, may help move DRF management toward more personalized and evidence-based care.

TREATMENT AND COMPLICATIONS OF DISTAL RADIUS FRACTURES

Regardless of whether instability can be accurately predicted, the central clinical question remains: how should we manage these unstable and complex DRFs? The second part of this thesis explored optimal management for such fractures, focusing on surgical intervention and addressing potential complications to improve patient counseling and outcomes.

An unstable and multi-fragmented DRF; what to do?

As shown in the first part of this thesis, CT is a valuable diagnostic tool, particularly in these unstable, intra-articular and multi-fragmented DRFs. A critical element within these fractures is the dorsal ulnar corner (DUC) fragment, which is particularly prone to displacement and challenging to fixate. Its instability may contribute to distal radioulnar joint (DRUJ) instability, loss of range of motion (ROM), and radiocarpal instability (21, 22).

While Dutch guidelines do not explicitly recommend either volar or dorsal plating in such complex DRFs, the volar approach is generally favored due to its less invasive nature and lower risk of tendon damage (23-26). Previous studies have primarily evaluated the use of single volar locking plates in achieving union without loss of reduction, regardless of DUC fragment size. These studies reported reduction loss rates ranging from 0% to 13% but were generally based on small sample sizes (27-31). **Chapter 6** of this thesis further investigated the effectiveness of single volar plate with the use of a dorsal bone clamp as an "scaffold fixation" for DRF stabilization, underscoring its ability to maintain fracture alignment in complex, multi-fragmented cases with a DUC fragment. The findings demonstrate that "scaffold fixation" effectively preserves radiocarpal alignment and supports satisfactory range of motion, regardless of whether the DUC fragment receives fragment-specific fixation and regardless of DUC fragment size. This insight is clinically significant, as shorter screws may reduce the risk of extensor tendon irritation or intra-articular screw placement, a leading cause of hardware removal in volar plating. Furthermore, as discussed in Part I, more frequent use of CT imaging may improve surgical planning in comminuted

fractures, especially for better visualization of the "four corner" concept and guiding the placement of shorter screws in the DUC fragment.

Counseling for operative treatment of DRF; what can the patient expect?

Proper plate choice, positioning, screw length, and overall fixation strategy, as shown in **Chapter 6**, are essential to prevent postoperative complications following volar plate fixation for DRFs. Building on this, **Chapter 7** further examined the nature and frequency of complications, particularly those leading to hardware removal. The findings show increased hardware removal rates over the past decade. Tendon irritation or rupture, especially involving the flexor tendons, and intra-articular screw placement were identified as the most common reasons for hardware removal, accounting for approximately 33% to 62% of cases. Plate and screw positioning is a known contributing factor for hardware related complications: hardware placed too distally, beyond the watershed line, risks damaging flexor tendons, while plates positioned too proximately may compromise fracture stability, particularly in complete intra-articular patterns (32, 33).

Several additional factors may explain the growing trend in hardware removals. These include increased patient awareness of potential complications and a healthcare environment emphasizing shared decision-making and patient autonomy. Patients today are more engaged and informed and are more likely to opt for hardware removal when facing symptoms such as pain, stiffness, or functional limitation (34-37). While increased patient awareness can be beneficial to the shared decision-making process, it also carries the risk of unnecessary hardware removal in the absence of clear complications or clinical indications. Patients today are more likely to seek information independently, for example through online sources, which may lead to misconceptions about the role of hardware in persistent symptoms such as pain or stiffness. Although shared decision-making remains essential, thorough patient counselling will become increasingly important to help manage expectations and prevent unnecessary procedures. Future research should further explore how patient perceptions influence the decision to remove hardware.

Chapter 7 also demonstrated that most hardware removals occur within the first postoperative year, highlighting this period as a critical window for follow-up and patient counseling. Particularly in patients with intra-articular fracture extension, the risk of hardware removal is shown to be three times higher. This may reflect the greater complexity of these fractures, where precise screw placement in key fragments is crucial and can still lead to protruding screws or secondary displacement of crucial fragments. These findings underscore the importance of proactive and individualized counseling before and after surgery, including discussion of the potential need for hardware removal, especially in high-risk patients.

To reduce complication rates and ultimately minimize the need for hardware removal, optimizing the initial surgery is essential. Strategies such as preoperative CT-based planning, precise plate positioning, and the use of shorter screws in critical areas, such as the DUC (**Chapter 6)** should be emphasized. Several technical steps can lower the risk of hardware-related symptoms and subsequent removal. Examples are bicortical drilling of distal screws with subsequent 2-mm back-out, accurate plate placement according to the Soong classification, and lateral fluoroscopy at approximately 21° to detect intra-articular screws or malalignment. Intraoperative 3D imaging can further evaluate alignment and plate position.

Although malunion is a well-known complication of DRFs, nonunion is a rare but more severe complication after fixation. **Chapter 8** of this thesis described outcomes following surgical repair of DRF nonunion and found that reoperation was required in 25% of cases. The primary causes of reoperation were infection, persistent nonunion, and hardware removal. These findings highlight the clinical burden and complexity of managing nonunions, particularly in patients with comorbidities such as smoking or poor bone quality. Accurate risk stratification and thorough preoperative counseling before surgical repair of nonunions are essential, especially considering the high stakes associated with revision surgery.

Where do we stand now?

As this thesis demonstrates, either short or long screw purchase in the dorsal ulnar corner in complex DRFs has no significant effect on ROM or radiocarpal alignment.

Given the importance of preventing hardware removal, future management should prioritize refining volar plate design, ensuring precise plate and screw placement, and detecting hardware-related complications at an early stage. This is not only essential to avoid unnecessary reoperations but also to reduce the burden on an already strained healthcare system facing rising costs and personnel shortages. Thorough counseling regarding potential complications, including hardware removal, nonunion, and the possibility of revision surgery following nonunion repair, remains essential.

A more personalized approach, such as tailor-made and patient-specific plating using 3D planning, may help tailor fixation to each patient's unique anatomy. Techniques applied to the surgical management of DRFs can offer multiple benefits, including more precise surgical planning, enhanced fracture reduction, and optimized implant and screw placement. As a result, complications such as plate or screw irritation, secondary fracture displacement, tendon injury, implant failure, malunion, nonunion or even hardware removal, may be minimized (38, 39). Although 3D-assisted methods for surgical planning and development of patient-specific plates are still in the early stages of development, they show considerable potential for improving patient-centered care, decreasing complication rates, and refining the accuracy of screw placement and length (40). However, whether these radiological advantages translate into meaningful clinical benefit and justify the associated costs remains unclear, beyond the scope of this, this should be considered a current limitation and subject for future research.

What are we aiming for in the future?

Scaffold fixation with a volar plate and dorsal bone clamp or selective fragment-specific approaches may reduce the hardware related risks by stabilizing only the most critical fragments. Further prospective studies comparing scaffold fixation with fragment-specific techniques are warranted to determine whether less extensive hardware leads to fewer complications, reduced reoperation rates, improved stabilization, and better overall patient outcomes.

Early discussions regarding the risks of malunion, nonunion, tendon complications, and potential hardware removal can foster realistic expectations and more informed decision-making. However, the main goal should be to prevent these complications and re-interventions. Future research should further focus on the predictive factors associated with these complications.

The mental and emotional burden of hardware complications and prolonged recovery for the patient should not be underestimated. Patient-reported outcomes must play a central role in evaluating treatment success and should be a subject for further research.

While nonunion itself is relatively rare and this study only assessed a limited number of cases, its consequences can be significant, and further research is needed to identify predictive factors and optimize treatment pathways.

Clinicians can better tailor management to each individual's needs by refining diagnostic techniques by enhancing CT and improve surgical strategies, reducing complication rates, minimize reoperations, and enhance the long-term functional outcomes of individuals with complex DRFs.

LIGAMENTOUS INSTABILITY IN THE WRIST

The third part of this thesis has broadened the scope by exploring ligamentous instability, a more subtle yet equally critical component of carpal stability. This shift in focus from bone to soft tissue reflects a growing understanding in wrist surgery: osseous alignment and fixation are only part of the story. Achieving and maintaining joint stability requires anatomical reduction of the bone and enhancement of the integrity of the surrounding ligamentous structures, which are crucial for long-term stability, function, and good patient outcomes. Thus, Part III of this thesis offered a deeper investigation at the complex biomechanical relationships between the carpal bones, bridged and balanced by both intrinsic and extrinsic ligaments.

When should we use an MRI to assess suspected SLIL injury?

While scapholunate dissociation is the number one cause of traumatic carpal instability, yet many patients, especially older adults, do not recall any specific trauma (41-45). As demonstrated in **Chapter 9**, this thesis found that 51% of patients with SLIL injury assessed on MRI had no recollection of a trauma. More strikingly, SLIL pathology was commonly observed in patients with low clinical suspicion. This raises critical questions for daily practice:

- If SLIL injuries are frequently found in patients with low clinical suspicion, is MRI even necessary in these cases?
- Can MRI lead to the overdiagnosis of potentially asymptomatic SLIL injuries?

Age appears to be a major effect modifier. Prior work has shown a higher incidence of asymptomatic SL dissociation on radiographic assessment with increasing age (46, 47). The findings of this thesis demonstrated that SLIL injuries were more frequently observed in older patients, especially among those without an antecedent injury and with low clinical suspicion. In such individuals, SLIL signal change is likely to reflect age-related degeneration or chronic, non-progressive pathology and, in the absence of pain, mechanical symptoms, or functional impairment, typically does not warrant intervention. These findings argue against routine MRI in older patients with low pre-test probability, where imaging may promote overdiagnosis and downstream overtreatment without improving outcomes.

Conversely, the threshold for MRI should be lower in younger patients who present with substantial symptoms and a clear history of trauma. In this higher pre-test probability context, MRI can refine diagnosis, show the extent of ligament injury, and help in early management decisions. Even then, imaging results should be integrated with clinical examination and functional assessment to determine intervention.

It is also important to separate anatomic injury from functional instability. Carpal instability is dynamic, and static modalities, MRI and CT, cannot directly capture pathologic motion. Historically, fluoroscopy provided real-time visualization of scapholunate widening during active motion but primarily reflects secondary osseous behavior rather than direct ligament integrity. This discrepancy raises a central diagnostic question: are we seeking to identify ligament injury, or are we aiming to detect functional instability? Emerging four-dimensional (4D) CT and 4D MRI techniques may bridge this gap by enabling time-resolved, three-dimensional evaluation of carpal kinematics during motion (48, 49).

SLIL dissociation in context: It's not just one ligament!

As **Chapter 9** focused on the diagnosis of SLIL injury, **Chapter 10** of this thesis investigated beyond the SLIL itself and demonstrated that an SLIL injury resulting in an SL diastasis often coexists with injury to one or more volar or dorsal extrinsic ligaments. Particularly, the long radio lunate (LRL), short radio luntate (SRL), and radioscaphocapitate (RSC) ligaments on the volar side, and the dorsal radiocarpal (DRC) and dorsal intercarpal (DIC) ligaments dorsally.

A key insight from this thesis is that isolated injuries to these extrinsic ligaments are significantly associated with SL diastasis and that their anatomical connections to and across the scaphoid and lunate, especially for the volar extrinsic ligaments, explain this relationship. Notably, this thesis accounted for coexisting volar and dorsal injuries, unlike previous studies (e.g., Ozkan et al.) that focused solely on dorsal ligaments, potentially underestimating the broader ligamentous involvement (50).

However, reliably assessing each individual extrinsic ligament remains difficult. As shown in our findings, inter-observer agreement for MRI evaluation of

these ligaments is low, which reflects the anatomical and technical limitations of current imaging protocols. Therefore, in clinical practice, it may be more realistic and generalizable to assess injury to volar extrinsic ligaments (LRL/ SRL/ RSC) and dorsal extrinsic ligaments (DIC and DRC) as functional groups rather than separately. Furthermore, partial SLIL tears frequently involve the proximal or volar portions of the ligament, which is not further assessed in this thesis. The volar component of the SLIL is not as robust as the dorsal component. After a volar SLIL tear, stability depends more on the volar extrinsic ligaments (e.g., RSC, LRL), if they are compromised as well, volar-sided scapholunate diastasis is likely.

Where do we stand now?

The findings of this thesis have practical implications for diagnosis and management of SLIL pathology. For older patients with low clinical suspicion and no antecedent trauma, MRI is usually low-yield for SLIL pathology and risks overdiagnosis; conservative, symptom-guided care is appropriate, with imaging reserved for persistent pain, mechanical symptoms, failure of non-operative treatment, or documented progression. For younger, symptomatic patients with a clear traumatic event, a lower threshold for MRI is justified to guide timely and targeted management. This strategy aligns imaging with clinical context, reduces unnecessary testing, and helps avoid treating incidental, asymptomatic SLIL findings.

Furthermore, MRI protocols and clinical assessments should explicitly consider volar and dorsal extrinsic ligaments as part of the diagnostic workup. Given the low agreement in MRI interpretation of individual ligaments, there is a need for standardized imaging criteria, possibly aided by advanced imaging software or AI applications. Routine MRI for all patients is not realistic considering rising healthcare costs. Surgical interventions often target the SLIL alone, typically through dorsal reconstruction or fixation. However, reconstruction or augmentation of surrounding extrinsic ligaments may improve long-term outcomes and should be considered in future approaches.

What are we aiming for in the future?

This thesis demonstrated low inter-observer agreement in evaluating individual extrinsic ligaments by MRI assessment. Future studies should focus on developing standardized MRI criteria for assessing both intrinsic and extrinsic ligaments. Including defining clear signal characteristics for partial versus complete tears and establishing thresholds for what constitutes clinically relevant findings on MRI.

While MRI remains valuable for identifying SLIL pathology its role should be understood as assessing structural integrity rather than functional stability. Still in early stages, dynamic 4D MRI allows non-invasive dynamic assessment with high spatial resolution, an subject for debate in future research (48).

Most surgical treatments for SL instability target only the SLIL, often through a dorsal approach. Clinical trials comparing traditional SLIL reconstructions with combined volar-dorsal extrinsic ligament augmentation may reveal differences in outcomes of preserving the SL distance, improving carpal stability, preserving ROM, lower reoperation rates, and long-term improvement of patient reported outcomes. Much of the literature focuses on radiographic or anatomical outcomes rather than patient experience. Qualitative and quantitative studies on pain, function, satisfaction, and return to activity after ligamentous wrist injury or reconstruction are essential.

WHAT IS 'THE BROAD SCOPE'?

Concomitant osseous and ligamentous injury

Traumatic wrist injury rarely involves bone alone. Especially in complex DRF patterns, concomitant ligamentous damage is common: arthroscopic series report acute SLIL lesions in 30–60% of patients (43, 51), and one study found that all AO type-C DRFs had injury to either the TFCC or the SLIL (52). However, the clinical significance of these lesions is variable (53). Not every ligament abnormality requires immediate intervention; management should be symptom- and stability-driven; "we treat patients, not images".

Beyond the SLIL injury, several intrinsic and extrinsic ligaments are critical to wrist stability and are frequently involved in DRFs. In radiocarpal fracture–dislocations, MRI studies have demonstrated complete ruptures of the volar RSC, LRL or SRL ligaments, as well as the DRC ligament (54). These injuries typically accompany high-energy intra-articular fractures and can contribute to instability if left entirely unprotected. That said, accumulating evidence suggests that many concomitant ligament lesions in the DRF setting do well without immediate repair, which argues against routine, comprehensive intra-operative "mapping" or repair in all cases. A pragmatic, stepwise diagnostic strategy, driven by clinical suspicion, mechanism, and fracture pattern, therefore seems preferable. Advanced imaging should be used selectively: MRI is valuable for detecting acute intrinsic and extrinsic tears (55), while CT remains the modality of choice for fracture detail. Instability is dynamic, so static images have limits. Dynamic options such as 4D CT/MRI or high-quality wrist ultrasound, with selective arthroscopy, may help. For now, use clinical risk to decide when CT or MRI will change management, and add dynamic imaging when it is available and likely to matter.

Additionally, in asymptomatic or incidental intra-operative findings without mechanical signs of instability, planned follow-up is reasonable; intervention should be reserved for persistent symptoms, objective (dynamic or progressive) instability, or failure of conservative care. A more feasible and cost-effective diagnostic strategy should rely on a stepwise approach guided by clinical suspicion and fracture pattern, to guide the selective use of advanced imaging and improve outcomes.

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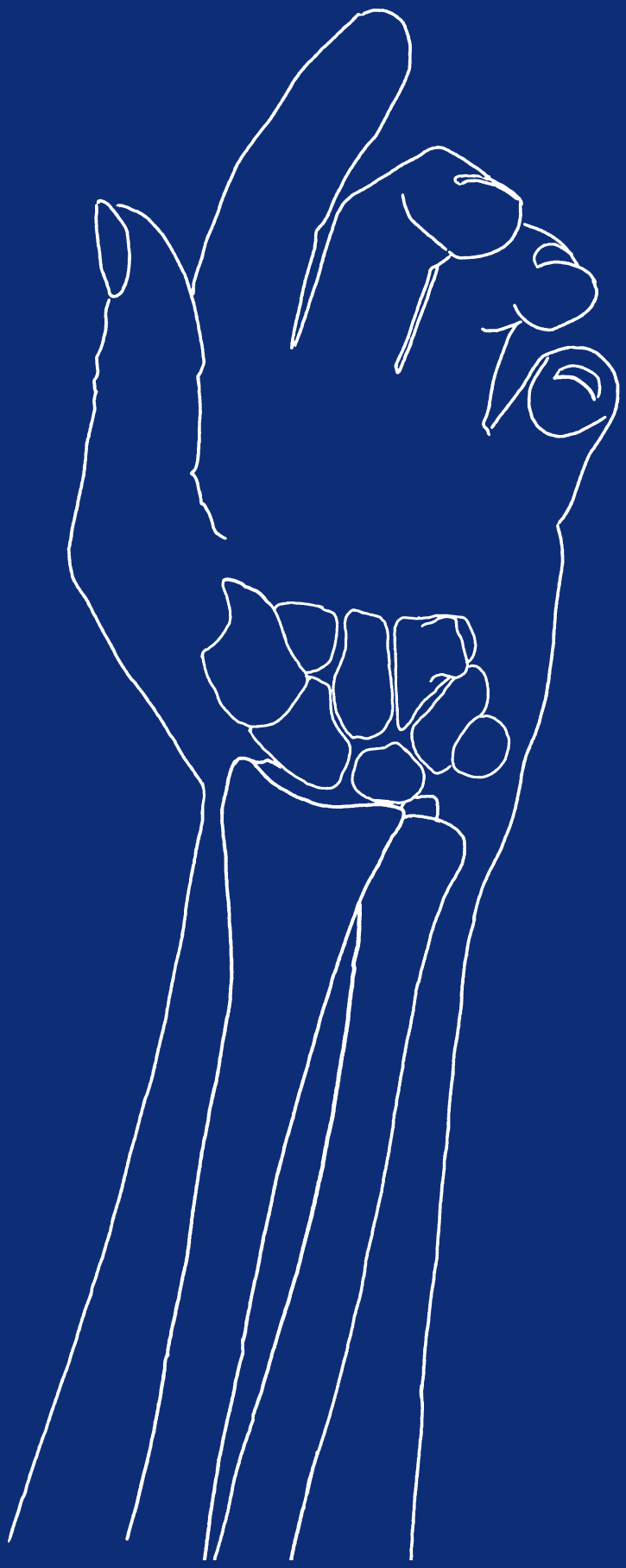


CHAPTER 12

Summary and conclusion
Nederlandse samenvatting en conclusie

SUMMARY

Chapter 1 is the general introduction of this thesis. It outlines the anatomical aspects of distal fractures and gives insight into the diagnosis, treatment, outcomes, and complications. Furthermore, it describes the ligamentous framework of the scapholunate ligament, the intrinsic and the extrinsic ligaments in the wrist.

Chapter 2 examines the role of CT compared with conventional radiography in assessing fracture alignment after closed reduction of DRFs. Of the 96 included patients with adequate alignment on initial post-reduction radiographs, CT assessment revealed malalignment in 51 patients (53%). The discrepancies were most pronounced in intra-articular parameters: step-off and gap on CT led to reclassification of the majority of fractures from "aligned" to "malaligned." Among patients with malalignment on CT, 73% underwent operative treatment.

Conclusions

- CT scanning after reduction frequently reveals malalignment in DRFs that appear adequately aligned on radiographs.
- The main driver of this discrepancy is intra-articular incongruency detected on CT imaging.
- When doubt exists about post-reduction alignment, CT imaging provides additional diagnostic value and may guide surgical decision-making.

Chapter 3 provides a systematic review of literature on the application of AI, specifically convolutional neural networks (CNNs), in the evaluation of DRFs. A total of 576 studies were screened, of which 15 were included. For fracture detection, reported sensitivity and specificity ranged from 80% to 99% and 73% to 100%, respectively. The AUC varied from 0.87 to 0.99, with accuracies between 82% and 99%. For fracture classification, accuracies ranged from 60% to 81% and AUC values from 0.59 to 0.84. None of the included studies addressed prediction of loss of threshold alignment, despite its high clinical relevance.

Conclusions

- CNN-based AI models demonstrate high accuracy and diagnostic performance for DRF detection on radiographs.
- Performance of AI algorithms for fracture classification is modest and less consistent.
- No studies have yet developed or validated algorithms to predict secondary displacement or loss of alignment in DRFs.

Chapter 4 and **5** examine surgeons' ability to predict loss of threshold alignment (instability) after closed reduction of DRFs. Two randomized Science of Variation Group experiments were conducted: in Chapter 4, 116 surgeons assessed 20 DRF cases on radiographs; in Chapter 5, 115 surgeons assessed 15 cases on radiographs with or without post-reduction CT.

The diagnostic accuracy for predicting loss of alignment was 55% (95% CI: 46–62%) when surgeons viewed both pre- and post-reduction radiographs, compared to 54% (95% CI: 51–57%) when only post-reduction radiographs were available.

Prediction accuracy improved slightly with the addition of CT (70%, 95% CI: 64–77%) compared to radiographs alone (67%, 95% CI: 61–73%), though this difference was not statistically significant. Patient factors (female sex and higher age) and surgeon factors (sex and years of experience) were modestly associated with probability estimations.

Conclusions

- Surgeons' ability to predict secondary displacement of DRFs after closed reduction is limited, whether using radiographs alone or in combination with CT imaging.
- Interobserver agreement for these predictions is consistently low.
- Patient factors (female sex, older age) and surgeon characteristics influence estimations but do not substantially improve accuracy.

- Given the restricted predictive value of radiographic and CT-based probability estimates, careful monitoring of adequately reduced DRFs during immobilization remains essential.

Chapter 6 evaluates the outcomes of scaffold fixation with volar locking plates in intra-articular DRFs with preoperatively identified DUC fragments. In this study of the ICUC® database, 87 patients were treated with a volar locking plate combined with temporary reduction using a dorsal bone clamp. Screw purchase in the DUC fragment (long vs. short) and DUC fragment size were compared with respect to radiocarpal alignment and functional outcome at follow-up. There were no significant differences in range of motion (flexion, extension, supination, pronation) between groups. DUC fragment size was not associated with screw purchase in the fragment or functional outcomes. Radiocarpal malalignment occurred in 2% of patients postoperatively and 7% at final follow-up, with no differences between screw purchase groups.

Conclusions

- Scaffold fixation with a volar locking plate and dorsal clamp effectively restores range of motion and maintains radiocarpal alignment in intra-articular DRFs.
- Neither screw purchase in the dorsal ulnar corner nor fragment size significantly affected clinical or radiographic outcomes.
- Routine fixation of the DUC fragment may not be essential when scaffold fixation is applied.

Chapter 7 investigates changes in volar plate removal rates and indications over a ten-year period. In this retrospective cohort study, 771 DRFs treated with a volar plate between 2006–2007 and 2016–2017 were analyzed. The overall implant removal rate was 7.5%. Removal was more frequent in 2016-2017 (9.3%) compared with 2006-2007 (5.6%, p=0.02). Multivariable analysis identified 2016-2017 (HR 1.95, 95% CI 1.13–3.37, p=0.016) and intra-articular fracture involvement (HR 3.01, 95% CI 1.20–7.55, p=0.019) as independent risk factors for implant removal. Indications for removal shifted:

tendon complications increased from 33% in 2006-2007 to 62% in 2016-2017 while intra-articular screw placement decreased from 33% to 8%.

Conclusions

- Implant removal after volar plate fixation of DRFs has become more frequent over the past decade.
- Intra-articular fracture involvement is an independent risk factor for implant removal.
- Indications for implant removal have shifted: fewer cases are due to screw placement errors, while tendon-related complications are increasingly dominant.
- Despite improved implant placement techniques, rising removal rates highlight the ongoing clinical impact of tendon complications.

Chapter 8 evaluates reoperation and complication rates following distal radius nonunion repair. In this study, 33 adult patients underwent open reduction and internal fixation for distal radius nonunion between 2005 and 2021. Unplanned reoperations occurred in 8 of 33 patients (24%). The main reasons were infection requiring irrigation and debridement, revision surgery for persistent nonunion, and unplanned hardware removal. A total of 10 complications were reported in 9 patients, most commonly infection and persistent nonunion.

Conclusions

- Reoperations are required in approximately one of four patients undergoing distal radius nonunion repair.
- The most frequent complications are infection and persistent nonunion.
- Patients should be counseled about the relatively high risk of reoperation and complications when undergoing surgical treatment for distal radius nonunion.

Chapter 9 investigates the prevalence of scapholunate interosseous ligament (SLIL) signal changes on wrist MRI. In 1,021 patients undergoing wrist MRI or MR arthrography, SLIL signal changes were identified in 317 patients (31%). Notably, 264 of these (83%) had a low clinical suspicion for SLIL pathology. The prevalence of SLIL signal changes increased with age: from 15% in patients aged 18–30 years to 50% in those over 70 years. Among the 317 patients with SLIL signal changes, 161 (51%) had no history of wrist trauma. In this subgroup, the prevalence ranged from 28% in young adults to 80% in patients older than 70 years.

Conclusions

- SLIL signal changes are common on wrist MRI, particularly in older patients and in those without prior trauma.
- In younger patients, SLIL changes on MRI are less prevalent and may be more clinically meaningful.
- In older patients, SLIL changes are frequently incidental and may not reflect acute pathology.
- Clinicians should interpret MRI findings of SLIL pathology with caution, especially in the context of age and clinical suspicion.

Chapter 10 examines the association between extrinsic ligament injury and scapholunate (SL) diastasis in patients with MRI-confirmed SL ligament injury. In this study MRI's of a total of 101 patients (2018–2023) were independently assessed by three musculoskeletal radiologists, for injuries to volar extrinsic ligaments (LRL, SRL, RSC), dorsal extrinsic ligaments (DIC, DRC), and the scaphotrapeziotrapezoidal (STT) ligament, as well as the degree of SL diastasis. In patients with SL diastasis >2 mm, volar extrinsic ligament injuries were present in 42% compared with 11% in those without diastasis. Dorsal extrinsic ligament injuries were observed in 60% of patients with diastasis compared to 25% without. Both volar and dorsal extrinsic ligament injuries were independently associated with SL diastasis (OR 4.44 and 3.39, respectively; $p<0.05$). Inter-observer agreement was fair to moderate for injured ligaments, and substantial for uninjured extrinsic ligaments.

Conclusions

- Both volar and dorsal extrinsic ligament injuries are independently associated with SL diastasis >2 mm.
- Injury patterns extend beyond the intrinsic SL ligament, highlighting the importance of assessing extrinsic ligament status on MRI.

Finally, the general discussion and future perspectives are discussed in **Chapter 11**.

CONCLUSION

This thesis broadens the perspective on wrist pathology: from fracture mechanics, through fixation strategies and hardware-related complications in distal radius fractures, to the ligamentous framework that sustains joint stability beyond the bone. It argues for the routine use of CT imaging to refine diagnosis, enable fragment-specific classification, and predict loss of alignment after reduction, potentially aided by AI. This thesis describes sufficient surgical planning by "scaffold" screw placement in the DRFs and provides deeper insight in hardware related complications or reoperations. Furthermore, it highlights the underappreciated role of extrinsic ligaments in scapholunate instability. Together, these studies advocate an integrated, patient-centered, evidence-based approach to wrist surgery.

The future of this field lies not only in refining diagnostic modalities or surgical techniques but also in understanding the wrist as a biomechanical unit and treating it as such. Future research should integrate the dynamic relationships among bone and ligament, structure and function, complication and recovery in the management of wrist injuries. With advanced imaging, precise fixation, and soft-tissue reconstruction, the next generation of wrist surgery can be more personalized and characterized by accurate diagnosis and by the prediction and prevention of wrist instability.

NEDERLANDSE SAMENVATTING

Hoofdstuk 1 bevat de algemene introductie van dit proefschrift. Hierin wordt de anatomie van de distale radius en de fractuur daarvan besproken, die is betrokken bij de stabiliteit of instabiliteit van de pols. Er wordt ingegaan op diagnostiek, behandeling, uitkomsten en complicaties van deze distale radiusfracturen. Daarnaast worden de betrokken ligamenten voor polsstabiliteit beschreven: het scapholunaire ligament en de volaire en dorsale extrinsieke ligamenten.

Hoofdstuk 2 onderzoekt de meerwaarde van CT-beeldvorming ten opzichte van conventionele röntgenfoto's bij de beoordeling van de stand na gesloten repositie van DRF's. Bij 96 geïncludeerde patiënten met een ogenschijnlijk adequate stand op de initiële röntgenfoto liet de CT-scan bij 51 patiënten (53%) een standsafwijking zien buiten de richtlijngrenzen. De discrepanties betroffen vooral intra-articulaire parameters voor fractuuruitlijning: op CT vastgestelde *step-off* en *gap* leidden vaak tot herclassificatie van "acceptabele" naar "onacceptabele" stand. Van de patiënten met een onacceptabele stand op CT werd 73% operatief behandeld.

Conclusies

- CT na repositie toont vaak een standsafwijking bij DRF's die op conventionele röntgenfoto's adequaat lijken gereponeerd.
- De belangrijkste oorzaak van deze discrepantie is intra-articulaire incongruentie, die op CT beter zichtbaar is.
- Bij twijfel over de stand na repositie biedt CT aanvullende diagnostische waarde en ondersteunt het de chirurgische besluitvorming.

Hoofdstuk 3 geeft een overzicht van de literatuur over AI, specifiek convolutionele neurale netwerken (CNN's), voor de beoordeling van DRF's. Van de 576 gescreende studies voldeden 15 aan de inclusiecriteria. Voor fractuurdetectie varieerden de uitkomsten als volgt: sensitiviteit 80–99%, specificiteit 73–100%, AUC 0.87–0.99 en accuratesse 82–99%. Voor fractuurclassificatie lag de accuratesse op 60–81% en de

AUC op 0.59–0.84. Geen enkele studie onderzocht het voorspellen van verlies van fractuurstand door AI, ondanks de duidelijke klinische relevantie daarvan.

Conclusies

- CNN-gebaseerde AI-modellen tonen een hoge diagnostische nauwkeurigheid voor fractuurdetectie op röntgenfoto's.
- De prestaties van AI voor fractuurclassificatie zijn wisselend en beduidend lager dan voor fractuurdetectie.
- Er zijn nog geen AI-algoritmen ontwikkeld of gevalideerd voor het voorspellen van secundaire dislocatie bij DRF's.

Hoofdstuk 4 en 5 onderzoeken het vermogen van chirurgen om verlies van fractuurstand (instabiliteit) na gesloten repositie van DRF's te voorspellen. In twee scenario-gebaseerde, gerandomiseerde experimenten van de Science of Variation Group beoordeelden 116 chirurgen 20 DRF-casussen op röntgenfoto's (Hoofdstuk 4) en 115 chirurgen 15 DRF-casussen op röntgenfoto's, met of zonder aanvullende post-repositie-CT (Hoofdstuk 5).
De diagnostische nauwkeurigheid voor het voorspellen van verlies van stand bedroeg 55% (95%-CI: 46–62%) bij beoordeling van pre- en post-repositie röntgenfoto's, tegenover 54% (95%-BI: 51–57%) bij uitsluitend post-repositiebeelden. Het toevoegen van CT verhoogde de nauwkeurigheid licht van 67% (95%-CI: 61–73%) naar 70% (95%-CI: 64–77%), maar dit verschil was niet statistisch significant. Patiëntkenmerken (vrouwelijk geslacht, hogere leeftijd) en chirurgkenmerken (geslacht, aantal jaren ervaring) waren zwak geassocieerd met de inschatting.

Conclusies

- Het vermogen van chirurgen om secundaire dislocatie na gesloten repositie van DRF's te voorspellen is beperkt, zowel op röntgenfoto's als met aanvullende CT.

- De interobserverovereenkomst tussen de chirurgen voor het voorspellen van secundaire dislocatie is laag.
- Patiënt- en chirurgkenmerken beïnvloeden de inschatting, maar verbeteren de nauwkeurigheid niet wezenlijk.
- Vanwege de beperkte voorspellende waarde van röntgenfoto's en CT blijft zorgvuldige follow-up tijdens gipsimmobilisatie essentieel.

Hoofdstuk 6 beoordeelt de uitkomsten van "scaffold fixatie" met een volaire plaat bij intra-articulaire DRF's met een dorsaal-ulnaire hoek (DUC)-fragment. In de ICUC®-database-studie werden 87 patiënten geïdentificeerd die werden behandeld met een volaire plaat, gecombineerd met tijdelijke repositie met een dorsale bot klem (scaffold). De schroeffixatie in het DUC-fragment (lang versus kort) en de fragmentgrootte werden vergeleken met de radiocarpale stand en de functionele uitkomsten bij follow-up. Tussen de groepen werden geen significante verschillen gevonden in bewegingsuitslag (flexie, extensie, supinatie, pronatie). De DUC-fragmentgrootte was niet geassocieerd met de mate van schroeffixatie of met functionele uitkomsten. Bij 2% werd postoperatief een radiocarpale stand afwijking gezien en bij 7% bij de laatste follow-up. Dit verschilde niet tussen patiënten met lange versus korte schroeven in het DUC-fragment.

Conclusies

- "Scaffold fixatie" met een volaire plaat en dorsale klem herstelt de bewegingsuitslag effectief en behoudt de radiocarpale stand bij intra-articulaire DRF's.
- Noch de mate van schroeffixatie in de dorsaal-ulnaire hoek, noch de fragmentgrootte had een significante invloed op klinische of radiologische uitkomsten.
- Routinematige fixatie van het DUC-fragment lijkt niet noodzakelijk wanneer scaffold-fixatie wordt toegepast.

Hoofdstuk 7 beschrijft de ontwikkeling van het aantal implantaatverwijderingen en de indicaties voor verwijdering over een periode van tien jaar. In een retrospectieve cohortstudie werden 771 DRF's geanalyseerd die met een volaire plaat waren gefixeerd in 2006–2007 en 2016–2017. Het totale percentage implantaatverwijdering bedroeg 7,5%. Het percentage implantaatverwijderingen was significant hoger in 2016–2017 (9,3%) dan in 2006–2007 (5,6%; p=0,02). In multivariabele analyse waren de behandelperiode 2016–2017 (HR 1.95; 95%-CI 1.13–3.37; p=0.016) en intra-articulaire fractuurbetrokkenheid (HR 3.01; 95%-CI 1.20–7.55; p=0.019) onafhankelijke risicofactoren voor het verwijderen van de plaat. De indicaties veranderden over een periode van 10 jaar: pees gerelateerde complicaties namen toe (van 33% naar 62%), terwijl verwijdering door intra-articulaire schroeven afnam (van 33% naar 8%).

Conclusies

- De incidentie van materiaalverwijderingen na volaire fixatie van DRF's is de afgelopen tien jaar toegenomen.
- Intra-articulaire fractuurbetrokkenheid is een onafhankelijke risicofactor voor het verwijderen van implantaten.
- Indicaties voor plaatverwijdering zijn veranderd: minder vaak door intra-articulaire schroeven, maar vaker bij pees gerelateerde complicaties.

Hoofdstuk 8 analyseert re-operaties en complicaties na operatieve behandeling van niet genezen (non-union) distale radius fracturen. In totaal ondergingen 33 volwassen patiënten een open repositie en interne fixatie (ORIF) bij non-union fracturen tussen 2005 en 2021. Ongeplande re-operaties kwamen voor bij 8 van de 33 patiënten (24%). Belangrijkste redenen waren infectie (wondspoelen en weefselverwijdering), revisiechirurgie wegens persisterende non-union, en ongeplande verwijdering van implantaten. In totaal werden 10 complicaties beschreven bij 9 patiënten, het vaakst infectie (n=3) en persisterende non-union (n=3).

Conclusies

- Ongeplande re-operaties zijn noodzakelijk bij circa één op de vier patiënten na reeds operatieve behandeling van distale radius non-union.
- De meest voorkomende complicaties zijn infectie en persisterende non-union.

Hoofdstuk 9 onderzoekt de prevalentie van scapholunair interosseous ligament (SLIL)-pathologie in de pols op MRI. Bij 1.021 patiënten die een MRI of MR-artrogram ondergingen, werd bij 317 patiënten (31%) SLIL-pathologie vastgesteld. Van deze groep had 83% een lage klinische verdenking op SLIL-pathologie. De prevalentie nam toe met de leeftijd: van 15% bij 18–30 jaar tot 50% bij patiënten ouder dan 70 jaar. Onder alle 317 patiënten met SLIL-pathologie had 51% geen polstrauma in de voorgeschiedenis. In deze subgroep varieerde de prevalentie van 28% bij jonge volwassenen tot 80% bij patiënten ouder dan 70 jaar.

Conclusies

- SLIL-pathologie komt frequent voor op MRI, vooral bij oudere patiënten en bij afwezigheid van trauma in de voorgeschiedenis.
- Bij jongere patiënten zijn deze afwijkingen minder gebruikelijk en daardoor waarschijnlijk klinisch relevanter.
- Bij oudere patiënten zijn SLIL-pathologie vaak een toevallige bevinding en niet altijd een teken van acute pathologie.

Hoofdstuk 10 onderzoekt de associatie tussen letsel aan de volair en dorsale extrinsieke ligamenten en SL-dissociatie bij patiënten met SLIL-letsel. In een retrospectieve multicenter-cohort van 101 patiënten (2018–2023) beoordeelden drie musculoskeletale radiologen de aanwezigheid van letsels van volair extrinsieke ligamenten (LRL, SRL, RSC), dorsale extrinsieke ligamenten (DIC, DRC), en het scaphotrapeziotrapezoïdale (STT) ligament, evenals de mate van SL-dissociatie. Bij patiënten met SL-dissociatie van >2 mm werd vaker volair extrinsieke ligamentenletsel gezien (42%) dan bij de patiënten zonder dissociatie (11%); bij de dorsale extrinsieke ligamenten was dit 60% versus 25%.

Zowel letsel aan de volair als dorsale ligamenten was onafhankelijk geassocieerd met SL-dissociatie >2 mm (OR 4.44 respectievelijk 3.39; $p<0.05$).

Conclusies

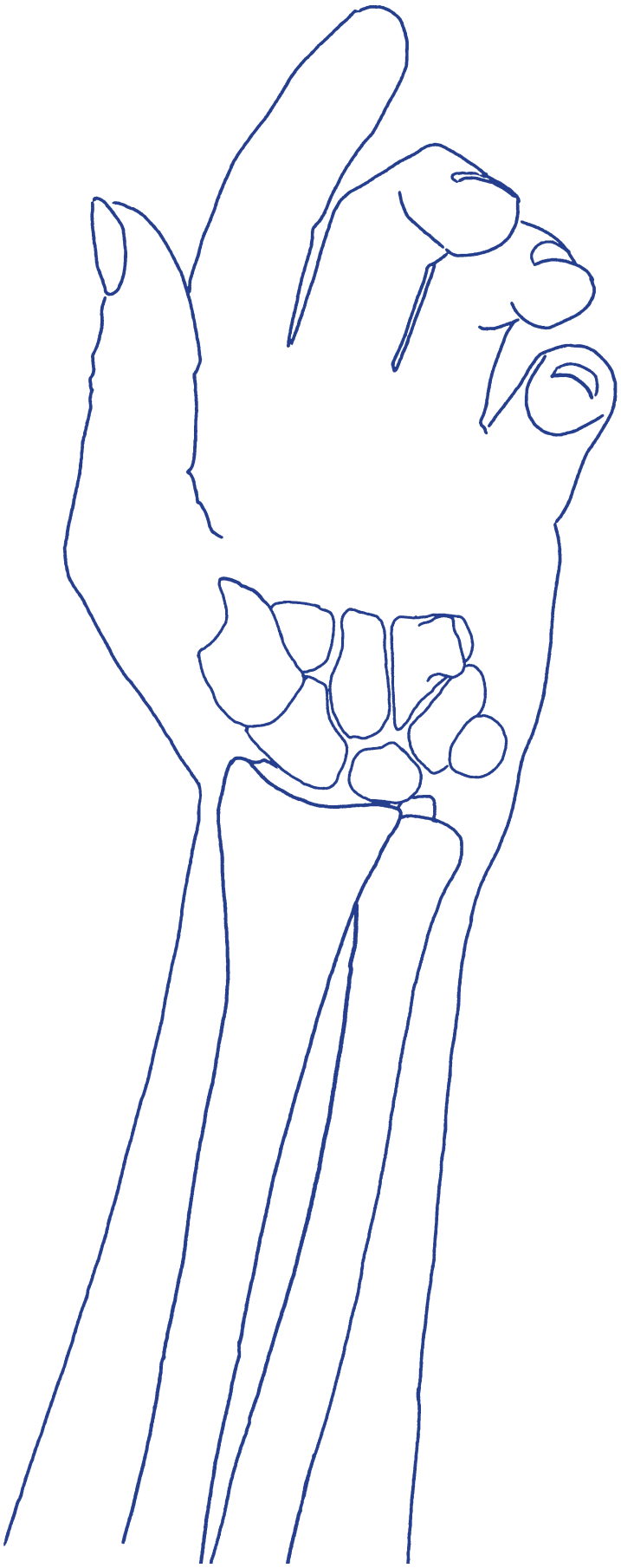
- Zowel volair als dorsale extrinsieke ligamentletsels zijn onafhankelijk geassocieerd met SL-dissociatie van >2 mm.

Hoofdstuk 11 bevat de algemene discussie en toekomstperspectieven.

CONCLUSIE

Dit proefschrift verbreedt het perspectief op polspathologie: van fractuur diagnostiek en voorspelling, fixatie technieken en implantaat gerelateerde complicaties bij distale radiusfracturen, tot het ligamentaire raamwerk dat gewrichtsstabiliteit waarborgt. Het pleit voor routinematiger gebruik van CT-beeldvorming om de diagnose te verfijnen, fragment specifieke classificatie mogelijk te maken en het risico op verlies van stand na repositie te voorspellen, eventueel ondersteund door AI. Verder wordt er een operatietechniek beschreven gebaseerd op 'scaffold'-schroefplaatsing bij DRF's, en wordt inzicht geboden in implantaat gerelateerde complicaties en her operaties. Daarnaast wordt de vaak onderschatte rol van extrinsieke ligamenten bij scapholunaire ligament instabiliteit belicht.

De toekomst van het vak ligt niet alleen in verdere verfijning van diagnostiek en operatietechnieken, maar ook in het begrijpen én behandelen van de pols als één biomechanische eenheid. Toekomstig onderzoek zou de dynamische samenhang tussen bot en ligament, tussen structuur en functie, en tussen complicatie en herstel integreren in de behandeling van polsletsels. Met geavanceerde beeldvorming, precieze fixatie en reconstructie van weke delen kan de volgende generatie polschirurgie meer gepersonaliseerd worden, gekenmerkt door nauwkeurigere diagnostiek en betere mogelijkheden om polsinstabiliteit te voorspellen en te voorkomen.



APPENDICES

Supplementary chapter

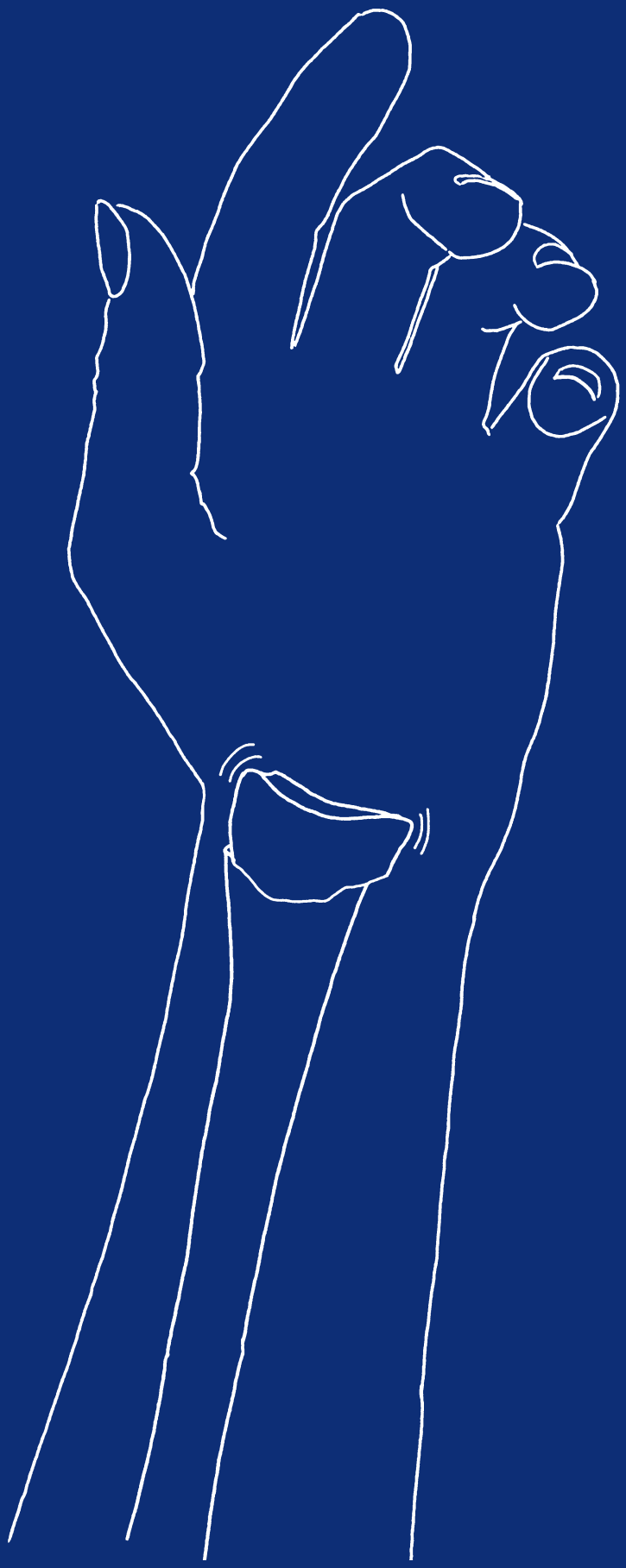
List of publications

Contributing authors

PhD portfolio

Dankelwoord

Letter to the author



SUPPLEMENTARY CHAPTER

Can surgeons accurately estimate loss of threshold alignment (instability) of distal radius fractures? The influence of imaging: diagnostic accuracy of radiographs versus computed tomography

Combined paper of chapter 4 and 5

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ABSTRACT

Aim

Almost half of distal radius fractures (DRF) lose threshold alignment (i.e., instability) after closed reduction and immobilization. This study aimed to investigate surgeons' ability to estimate secondary displacement, by addressing three questions:

1) What is the diagnostic accuracy of surgeons to estimate instability of DRFs on pre- and post-reduction radiographs?
2) What is the diagnostic accuracy of surgeons to estimate instability of DRFs on post-reduction Computed Tomography (CT) imaging?
3) What patient factors are associated with estimating instability?

Methods

We performed a scenario-based, randomized experiment with two distinct online surveys. In Part I, 116 members of The Science of Variation Group assessed radiographs of twenty initially displaced DRFs (11 "stable", 9 "unstable") and estimated the loss of threshold alignment after closed reduction. Half viewed pre- and post-reduction radiographs; half viewed only post-reduction radiographs. In Part II, 115 participants assessed fifteen DRFs cases (6 "stable", 9 "unstable") to estimate loss of alignment. Half of the participants evaluated pre- and post-reduction radiographs, and half also received post-reduction CT imaging.

Results

In Part I, diagnostic accuracy for estimating loss of threshold alignment on pre- and post-reduction radiographs was 54% (95% CI: 51%–57%), similar to 55% (95% CI: 46%–62%) when only viewing post-reduction radiographs (p=0.06). In Part II, the accuracy was 70% (95% CI: 64%–77%) with both radiographs and CT, versus 67% (95% CI: 61%–67%) with radiographs alone (p=0.24). Patient factors associated with estimating instability were female sex and higher age.

Conclusion

Surgeons' ability to detect DRF instability on both pre- and post-reduction radiographs as well as post-reduction CT-scans was limited, reflecting a restricted value of probability estimates for clinical decision-making. Given suboptimal estimations of alignment loss, it seems prudent to monitor adequately reduced fractures during initial immobilization. Future studies should focus on aids that can overcome this limited accuracy.

INTRODUCTION

Up to 50% of displaced distal radius fractures (DRFs) lose alignment beyond the established threshold after manual reduction and cast immobilization, according to guidelines (1-4). Surgeons may be accustomed to the terms “fracture instability” and “fracture re-displacement" rather than loss of threshold alignment. The terms "instability" and "re-displacement" imply a threshold of radiographic deformity and the judgment that the alignment of the DRF has surpassed that threshold. Loss of threshold alignment includes deformities such as volar or dorsal angulation, loss of inclination, positive ulnar variance, or the occurrence of an intra-articular step-off or gap. The degree of visible deformity, impaired function, and levels of discomfort and incapability can vary substantially for a given malunion (5-7). However, the fact that radiological outcome of a distal radius fracture might have limited clinical consequences especially for the elderly patient, informed consent and shared decision-making on treatment should be based on reliable information which emphasizes the need for accurate prediction tools to estimate the risk of re-displacement in cast. Since the decision to operate or not is not only based on the presence of objective parameters (e.g. alignment) at the time of consultation, but often also on the expectation that re-displacement beyond critical thresholds might occur during the conservative management.

Previous studies have identified several factors associated with re-displacement, including age, sex, degree of dorsal or volar comminution, ulnar variance, and dorsal angulation (1, 3, 4, 8, 9). MacKenney et al. (8) and Lafontaine et al. (10) have also proposed methods for prospectively predicting the radiographic outcome of a DRF using a formula or a set of five criteria, respectively. Regarding estimating loss of threshold alignment, one study noted poor diagnostic performance of the Edinburgh equation, whereas a separate study found good performance better than surgeon opinion alone (11, 12).

Additionally, the context of a radiological image might contain valuable information for a decision on future instability. Pre-reduction radiographs give insight into the degree of displacement and fragmentation. These factors may disappear in post-reduction radiographs. Additionally, computed tomography (CT) imaging may

depict fragmentation, displacement and deformity in more detail than plain radiographs, thus increasing the accuracy and reliability of estimates on loss of threshold alignment (13-17). One study found that CT scans improve inter-observer agreement on treatment recommendations for DRFs with a high therapeutic uncertainty, whereas inter-observer agreement decreases in DRFs with a high therapeutic certainty (18). However, the ability of surgeons to accurately estimate loss of thresholds alignment has not yet been evaluated.

Study questions

In this study, we aimed to answer the following questions: 1) What is the diagnostic accuracy of surgeons to estimate loss of threshold alignment (i.e. instability) of DRFs on plain radiographs (pre- and post-reduction)? 2) What is the diagnostic accuracy of surgeons to estimate loss of threshold alignment of DRFs on post-reduction CT imaging? 3) What patient factors are associated with estimating loss of threshold alignment?

METHODS

Study design

We conducted an IRB-approved, cross-sectional scenario-based study, in which members of the Science of Variation Group (SOVG) were invited to participate in two separate parts of the study with two different online experiments. Participating surgeons form the SOVG were blinded from the study design and hypothesis. To assess the diagnostic accuracy, participants assessed patients with initially displaced DRFs treated with closed reduction and cast immobilization and were asked to estimate loss of alignment beyond the thresholds presented in the AAOS modified Dutch guidelines, where the Dutch guidelines have some stricter thresholds, based on recent evidence (19, 20). In Part I, participating surgeons were randomized 1:1 to review either post-reduction radiographs alone or pre- and post-reduction radiographs. Several months later, in Part II, participating surgeons were randomized 1:1 to review either pre- and post-reduction radiographs alone or pre- and post-reduction radiographs with additional post-reduction CT imaging (coronal and sagittal view). Participation in Part I was not required nor obliged for participation in Part II.

Participants

The SOVG is a collaborative that studies variation in healthcare. The generalizability of SOVG scenario-based experiments is determined by variation in ratings sufficient to allow measurement of statistical associations. The relationships identified in a scenario-based experiment are likely reproducible in other samples with sufficient variation, while the absolute rates observed are probably not reproducible in other samples. SOVG members are orthopaedic, plastic, and general trauma surgeons who treat fractures in their daily practice. Most members practice in the United States or Europe. While everyone, from all over the world, is invited to join, and efforts to improve diversity have been made, most participating members are white men practising academics. Members receive group authorship or acknowledgement but no financial compensation for their contribution.

Patient selection and description of experiment

Suitable fractures were retrospectively and separately selected for both parts of the survey from two different level-1 trauma centers. Patients from Part I were treated in Hospital 1 between January 2017 and June 2020, and patients from Part II were treated in Hospital 2 between January 2011 and June 2020. Inclusion criteria for both surveys were: 1) reduced DRF, 2) ≥ 18 years at the time of injury, and 3) fracture alignment after reduction within acceptable thresholds according to the most recent AAOS modified Dutch guidelines (Table 1) (19). For Part I, patients were included if pre- and post-reduction radiographs and additional radiographs for a minimum of 6 weeks after injury were available, to determine loss of threshold alignment or not. For Part II, patients were included when pre- and post-reduction radiographs with additional post-reduction CT-scan within seven days and radiographs for a minimum of 6 weeks after injury, to determine loss of threshold alignment, or having a radiograph deemed to have threshold malalignment before surgery were available. The CT-scan was shown as a video in axial and sagittal view, form articular surface to sub metaphyseal region. Patients were excluded based on the following criteria: 1) operative treatment before losing threshold alignment, 2) prior ipsilateral DRF, 3) missing posteroanterior (PA) or lateral pre- and post-reduction radiographs, 4) radiographic obliquity impeding judgement and measurements. Patients were included by two researchers supervised by two orthopaedic surgeons and senior authors, not involved in the treatment either. Each researcher was responsible for one Part of the study. For all cases, fracture alignment was measured at trauma, post-reduction and follow-up, by two researchers supervised by two orthopaedic surgeons, to define whether its alignment was within acceptable limits according to the AAOS modified Dutch guidelines (Table 1) (19, 20). If not within threshold for any of the points in the guideline, at any of the available follow-up moments, this case was defined as "unstable". A total of twenty fractures were selected for Part I, of which eleven did not lose threshold alignment during follow-up ("stable"), and nine did lose threshold alignment ("unstable"). For Part II, fifteen fractures were selected, of which nine

eventually lost threshold alignment and six did not. See Table 2 for demographics of cases.

Table 1. Threshold for acceptable alignment according to the Dutch guidelines. A fracture has lost threshold alignment if one of the following measurements has been reached.

< 10° of dorsal angulation of the articular surface on a lateral radiograph
< 20° of volar angulation of the articular surface on a lateral radiograph
< 15° of ulnar ward inclination of the articular surface on the PA view (often referred to as radial inclination)
< 3 mm of ulnar positive variance
< 2 mm intra-articular step-off
No significant translation and intact radiocarpal alignment on the lateral radiograph
No significant translation on the PA radiograph

Table 2. Demographics of cases.

Variables	**Value***	
	Part I	**Part II**
N	20	15
Female	70% (14)	60% (9)
Age at trauma onset (years)	58 (±17)	53 (±20)
Side of trauma		
Left	55% (11)	53% (8)
Right	45% (9)	47% (7)
Fall mechanism		
Fall on wrist	75% (15)	60% (9)
Fall from height	20% (4)	13% (2)
Fall from bicycle	5% (1)	26% (4)
Surgical stabilization for DRF		
Yes	20% (4)	33% (5)
No	80% (16)	67% (10)

*Value is displayed as median with interquartile range for continuous non-parametric variables, as mean with standard deviation for continuous variables with normal distribution, and as number with percentage for categorial variables;

Response variables

All surgeons who participated reviewed the AAOS modified Dutch guidelines for acceptable alignment at the start of the online experiment (19, 20). For each of the fractures, the age at the time of trauma and sex (female or male) of the patient were presented. In Part II, the trauma mechanism was shown in the survey. Participants were asked, in their best estimate, if the fracture would lose alignment beyond the thresholds in the guidelines (i.e., deemed unstable) as a binary question (yes/no). No instructions were given on how to conclude on this prediction.

Explanatory variables

Explanatory participant variables were sex, continent where a surgeon practices, years of practice, whether a surgeon supervises surgical trainees, and subspecialty. In Part I, 116 participants completed the questionnaire, with 92% (107/116) being male, 43% (50/116) residing in the United States, and 36% (42/116) residing in Europe (Table 3). In Part II, 115 participants completed the questionnaire, with 90% (103/115) being male, 48% (55/115) residing in the United States, and 34% (41/115) residing in Europe (Table 3).

Statistical analysis

Accuracy, sensitivity, specificity, positive predictive value (PPV) and negative predictive value (NPV) were reported to describe participants' ability to predict loss of threshold alignment. An accuracy below 60% was considered poor, 60-70% moderate, 70-90% good and above 90% excellent (21). The accuracy was calculated by comparing the online experiment outcomes (predicted instability yes/no) to the alignment on the follow-up radiographs (proven instability present/absent), measured according to the Dutch guidelines (19). A mixed multilevel logistic regression analysis was used to evaluate patient factors (sex, fall mechanism and age) associated with dichotomous prediction of threshold loss of alignment accounting for nesting by surgeons. The alpha was set at 0.05.

Table 3. Part I and **Part II:** Demographics of participants

Variables	**Value***	
	Part I	**Part II**
N	116	115
Male	92% (107)	90% (103)
Continent		
US	43% (50)	48% (55)
Europe	36% (42)	35% (41)
Other	21% (24)	17% (19)
Years of practice		
0 - 5	25% (29)	23% (26)
6 - 10	22% (25)	19% (22)
11 - 20	30% (35)	33% (38)
21 - 30	23% (27)	25% (29)
Supervising	82% (95)	80% (92)
Subspecialty		
Fracture surgeons	43% (50)	37% (43)
Upper extremity surgeons	44% (52)	49% (56)
Other	12 % (14)	15% (16)
Randomization groups		
Group 1[a]	52% (60)	56% (64)
Group 2[b]	48% (56)	44% (51)

Value is displayed as median with interquartile range for continuous non-parametric variables, as mean with standard deviation for continuous variables with normal distribution, and as number with percentage for categorial variables;

[a.] In Part I participants in this group were shown only post-reduction radiographs, in Part II of pre-and post-reduction radiographs.

[b.] In Part I participants in this group were shown pre- and post- reduction radiographs, in Part II of pre-and post-reduction radiographs with CT imaging.

RESULTS

Part I: Accuracy in estimation of loss of threshold alignment on radiographs

Participants assessing pre- and post-reduction radiographs demonstrated an accuracy of 54% (95% Confidence Interval [CI]: 46%–62%). Sensitivity was 56% (95% CI: 53%–59%), specificity was 31% (95% CI: 28%–34%), with a PPV of 49% (95% CI: 46%–52%) and a NPV of 37% (95% CI: 34%–40%) (Table 4). When only post-reduction radiographs were evaluated, the diagnostic accuracy was 55% (95% CI: 51%–57%), with no significant differences compared to viewing both pre-and post-reduction radiographs (p=0.06). Sensitivity was 44% (95% CI: 42%–47%), specificity was 45% (95% CI: 42%–48%), with an PPV of 50% (95% CI: 47%–52%) and a NPV of 40% (95% CI: 37%–43%) (Table 4) The logistic regression model confirmed that viewing both pre- and post-reduction radiographs was not associated with a more accurate estimation of loss of threshold alignment (Odds ratio [OR]: 0.81; 95% CI: 0.65–1.0; p=0.063).

Part II: Accuracy in estimation of loss of threshold alignment on additional CT

For this second question participants demonstrated an accuracy of 70% (95% CI: 64%–77%) in estimating loss of threshold alignment in DRFs when pre- and post-reduction radiographs with additional CT is available. Sensitivity was 74% (95% CI: 70%–77%), specificity was 45% (95% CI: 39%–47%), with an PPV of 74% (95% CI: 70%–77%) and a NPV of 37% (95% CI: 33%–41%) (Table 5). When participants only viewed pre- and post-reduction radiographs of these cases, the diagnostic accuracy was 64% (95% CI: 61%–67%), showing a higher specificity (51%; 95% CI: 48%–54%) with a higher NPV of 45% (95% CI: 41%–48%) (Table 5). The logistic regression model confirmed that additionally viewing CT imaging was not associated with a more accurate estimation of loss of threshold alignment (OR: 1.1; 95% CI: 0.91–1.4; *p*=0.24).

Patient factors associated with estimating loss of threshold alignment

For part I: patient factors associated with surgeons' prediction of loss of threshold alignment were female patient sex (Regression Coefficient [RC]: -1.0; 95% CI: -1.3– -0.65; p <0.01), and older patient age (RC: 0.077; 95% CI: 0.67–0.86; p <0.01) (Table 6).

For part II similar results were found; patient factors associated with surgeon prediction of loss of threshold alignment were female patient sex (RC: 0.75; 95% CI: 0.52–0,98; p <0.01), and older patient age (RC: 0.013; 95% CI 0.0066–0.019; p <0.01) (Table 6).

Table 4. Part I Performance metrics of estimating loss of threshold alignment on radiographs

	Accuracy (%)*	**Sensitivity (95% CI)**	**Specificity (95% CI)**	**Positive predictive value (95% CI)**	**Negative predictive value (95% CI)**
Pre- and post-reduction radiographs	54% (46% - 62%)	56% (53% - 59%)	31% (28% - 34%)	49% (46% - 52%)	37% (34% - 40%)
Post-reduction radiographs	55% (51% - 57%)	44% (42% - 47%)	45% (42% - 48%)	50% (47% - 52%)	40% (37% - 43%)

*Value is displayed as a percentage with total amount of correct predictions/total amount of predictions; CI = Confidence Interval

Table 5. Part II Performance metrics of estimating loss of threshold alignment on radiographs and CT

	Accuracy (%)*	**Sensitivity (95% CI)**	**Specificity (95% CI)**	**Positive predictive value (95% CI)**	**Negative predictive value (95% CI)**
Pre- & post-reduction radiograph & CT	70% (64% - 77%)	68% (64% - 72%)	43% (39% - 47%)	74% (70% - 77%)	37% (33% - 41%)
Pre- & post-reduction radiograph	64% (61% - 67%)	65% (62% - 68%)	51% (48% - 54%)	71% (68% - 74%)	45% (41% - 48%)

*Value is displayed as a percentage with total amount of correct predictions/total amount of predictions; CI = Confidence Interval

Table 6. Mixed multi level level logistic regression analysis of patient factors associated with prediction of loss of threshold alignment Yes/No.

	Part I				**Part II**			
	Regression Coefficient (95% Confidence Interval)	**Standard Error**	**P-value**	**Δ Akaike**	**Regression Coefficient (95% Confidence Interval)**	**Standard Error**	**P-value**	**Δ Akaike**
Gender				28				26
Men	Reference value				Reference value			
Women	-1.0 (-1.3 to -0.65)	0.18	**<0.01**		0.75 (0.52 to 0.98)	0.12	**<0.01**	
Fall mechanism				28				27
High energy trauma	Reference value				Reference value			
Low energy trauma	18 (-232 to 267)	127,0	0.89		-0.22 (-0.49 to 0.046)	0.14	0.11	
Age	0.077 (0.67 to 0.86)	0.0048	**<0.01**	28	0.013 (0.0066 to 0.019)	0.0033	**<0.01**	29

Bold indicates statistical significance, P < 0.05. Δ Akaike indicates the model-fit, with lower scores indicating a better model fit

DISCUSSION

To guide DRF treatment effectively, it would be helpful to accurately estimate loss of alignment after reduction and immobilization. In answering the question if surgeons can accurately estimate this instability of DRFs, this study found that surgeons have limited accuracy in estimating loss of threshold alignment on both radiographs and CT imaging. Female sex and increased age were associated with estimating instability. From a clinical perspective, the inability to accurately assess the fracture can result in patients being immobilized in a cast for a longer period. In cases of secondary displacement of the radius fracture, surgery may still be required later. Patients whose fracture will not secondary displace might undergo an unnecessary surgery. This suggests that more insight and new techniques are needed to optimize the estimation of instability and, subsequently, early personalized treatment, including patient factors.

Limitations

This study has limitations. First, this is a survey-based online randomized experiment, which may not fully represent actual patient care. Participating surgeons were provided with radiographs, as well as age, sex, and for only Part II trauma mechanism. Other clinical aspects or patient characteristics were not shown in the surveys, as previous research indicates that these factors do not necessarily correlate with treatment recommendations (22).

Secondly, the included cases encompassed two different hospitals. However, both hospitals were comparable level-1 trauma centers with comparable populations. The requirement in Part II for CT imaging availability might have biased the selection towards cases already considered 'unstable', complicating the direct comparison between Part I and II. Nevertheless, this criterion aids in understanding a range of more complex or severe cases, potentially broadening the applicability of our findings to similar clinical situations.

Third, due to the retrospective design of this study, neither the specific type of immobilization (short-arm cast, circumferential cast, plaster splint, or sugar-tong splint) nor the quality of the casting could be assessed. According to the Dutch

guidelines, only short-arm immobilization is recommended for DRFs, either as a circumferential cast or a plaster splint. Moreover, a previous study demonstrated that the choice between circumferential casting and a plaster splint did not result in a significantly different rate of fracture redisplacement (2).

Lastly, the radiographic parameters used in the Dutch guidelines –used in both parts of this study - are somewhat arbitrary. Using other parameters might result in different estimations. However, these guidelines are evidence-based, have recently been revised in 2021, and align with other standards like the AAOS guidelines (19).

Can surgeons estimate loss of threshold alignment?

This study showed a poor accuracy in estimating loss of threshold alignment of DRF on pre- and post-reduction radiographs. There was no significant difference found in accuracy when participants assessed pre- and post-reduction radiographs compared to only assessing post-reduction radiographs. This highlights the fact that surgeons have limited accuracy in estimating the probability of loss of threshold alignment at all, independent of the radiographic information provided (8, 10, 23). Furthermore, this finding might indicate that the degree of displacement pre-reduction is not associated with post-reduction loss of threshold alignment. However, research to date has shown that there is a correlation between pre-reduction fracture position and post-reduction loss of threshold alignment. The Edinburgh Wrist Probability Calculator (EWC) uses pre-reduction radiographs to estimate the probability of loss of threshold alignment. However, the poor diagnostic performance (AUC of 0.47) and attempts to validate this tool suggest it may need more accuracy (3, 8, 12), which aligns with the current findings. In addition, one prior study reported a moderate accuracy of estimation of alignment loss on only radiographs (11). From this should be concluded that despite knowledge on risk factors for fracture instability and high-quality radiological investigations, surgeons are to date not able to predict distal radius instability with adequate accuracy.

Furthermore, Part II of this study showed that the surgeons have moderate accuracy in estimating loss of thresholds alignment with or without the addition of

post-reduction CT scans. The observation that assessing additional CT did not improve the moderate accuracy in estimation of loss of threshold alignment on only pre- and post-reduction radiographs might argue against its routine use. CT-scans are known for its ability to expose more detail on fragmentation and alignment of reduced DRFs; it did however not lead to more accurate predictions (24). One study found that CT-scan was associated with greater inter-observer agreement on treatment planning of fractures with high therapeutic uncertainty (18). Meaning that when considering surgery, surgeons consider using a CT for surgical planning.

When comparing the diagnostic accuracies of the two parts of our study (55% versus 70%), this showed a slight improvement in the accuracy of estimation of loss of threshold alignment when a CT scan was available. However, the direct comparison of accuracy's made between the two groups in Part II was not significant. This discrepancy may be attributed to the fact that Part II specifically included cases with a CT scan available. However, the including centers have a low threshold for making CT-scans in distal radius fracture care, this is not protocolized and reason for CT can be surgical planning rather than evaluation of alignment, introducing an inclusion bias for unstable fractures. Therefore, contrasting the poor accuracy of pre-and/or post-reduction radiographs from Part I with those enhanced by additional CT imaging in Part II provides a more accurate reflection of daily clinical practice and enhances the generalizability of the findings.

The observation that older patient age and female patient sex were associated with estimation of loss of threshold alignment is consistent with prior evidence that female and age are related to potential for loss of alignment, perhaps through increased degree of osteoporosis (1, 9, 25).

Current data show that the estimation of loss of threshold alignment by surgeons, despite knowledge on risk factors for instability, is insufficient for daily clinical practice. Future research should focus on techniques or models to further improve the reliability and accuracy of these estimations, taking these individual patient factors into account. Furthermore, using artificial intelligence (AI), particularly in the field of computer vision, might help to overcome these shortcomings (26, 27). An improved estimation of the probability for loss of threshold alignment, may

facilitate shared decision-making, in which we can highlight the importance of patient values and preferences, perceived invasiveness, and complications rather than discussing uncertain probabilities of radiographic outcome.

Conclusion

This survey-based randomized online experiment demonstrates limited accuracy in estimations of loss of threshold alignment of DRFs after closed reduction and cast immobilization in both pre- and post-reduction plain radiographs and with or without additional CT imaging, showing poor to moderate accuracy respectively. This underscores the need for new techniques to predict fracture displacement in the acute setting and to counsel patients with reliable information for optimal treatment. Ongoing advances in AI may offer decision-support tools that improve morbidity outcomes and efficiency, benefiting both individual patients and society.

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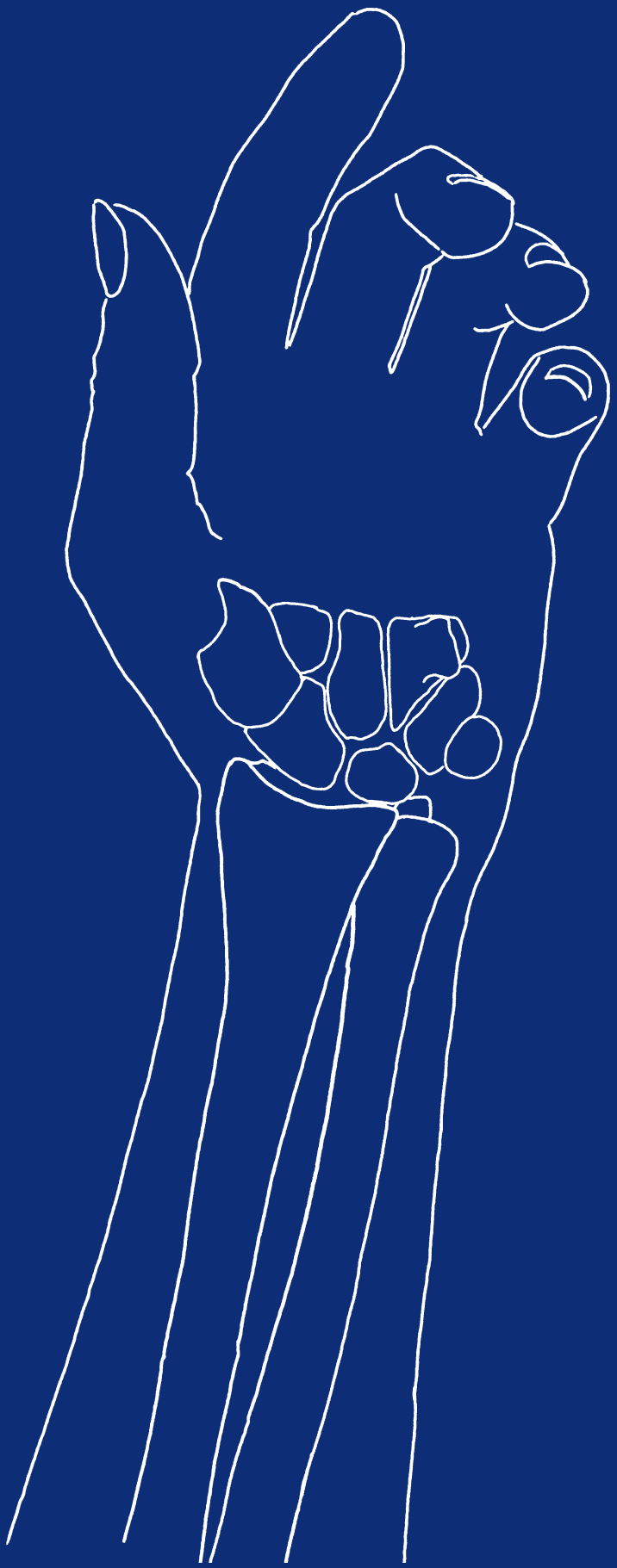

LIST OF PUBLICATIONS

Traditional radiography versus computed tomography to assess reduced distal radius fractures

Lente H.M. Dankelman, Britt Barvelink, Michael H.J. Verhofstad, Mathieu M.E. Wijffels, Joost W. Colaris

The European Journal of Trauma and Emergency Surgery 2024; 50(5):2313-2321
doi: 10.1007/s00068-024-02598-5

Artificial Intelligence for detection, classification and prediction secondary displacement of distal radius fractures on radiographs; a Systematic review

Lente H.M. Dankelman*, Koen D. Oude Nijhuis*, Jort P. Wiersma, Britt Barvelink, Frank F.A. IJpma, Michael H.J. Verhofstad, Job N. Doornberg, Joost W. Colaris, Mathieu M.E. Wijffels, Machine Learning Consortium

The European Journal of Trauma and Emergency Surgery 2024; 50(6):2819-2831
doi: 10.1007/s00068-024-02557-0

Can surgeons accurately estimate loss of threshold alignment (instability) of distal radius fractures? The influence of imaging: diagnostic accuracy of radiographs versus computed tomography

Lente H.M. Dankelman*, Koen D. Oude Nijhuis*, Melle M. Broekman, Frank F.A. IJpma, Britt Barvelink, Ruurd Jaarsma, Joost W. Colaris, Michael H.J. Verhofstad, Job N. Doornberg, David Ring, Mathieu M.E. Wijffels

Bone and Joint Open 2026;7(3):373-380 doi: 10.1302/2633-1462.73.BJO-2025-0330.R1.

Volar plate scaffold fixation of multi-fragmented intra-articular distal radius fractures: Fixation of the dorsal-ulnar corner

Lente H.M. Dankelman, Lucía Chiquiar, Magdalena Hartwich, Mathieu M.E. Wijffels, Alberto Fernández Dell'Oca, Jesse B. Jupiter, Abhiram R. Bhashyam

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Changes in incidence and indications for implant removal following volar plate fixation of distal radius fractures over 10 years

Lente H.M. Dankelman, Charlotte L.E. Laane, Mathieu M.E. Wijffels,
Michiel H.J.Verhofstad, Abhiram R. Bhashyam, Neal C. Chen
Under review at Journal of Orthopedic Trauma 2026

Factors associated with reoperation after distal radius nonunion repair

Mark Stam, Lente H.M. Dankelman, Mathieu M.E. Wijffels, Neal C. Chen, Abhiram R. Bhashyam, Charlotte L.E. Laane
Journal of Hand Surgery, American 2025 Jul; 50(7):889.e1-889.e8.
doi: 10.1016/j.jhsa.2024.07.001.

The prevalence of scapholunate signal abnormalities on magnetic resonance imaging

Kevin Kooi, Lente H.M. Dankelman, Kirsten Reikersdorfer, Huub H. de Klerk, Kamilcan Oflazoglu, Neal C. Chen
Hand (N Y). 2025 Sep 9:15589447251366675. doi: 10.1177/15589447251366675

Association of extrinsic ligament injury with diastasis in scapholunate ligament injury

Lente H.M. Dankelman, Kevin Kooi, Rene Balza Romeo, Jad Husseini,
Ambrose Huang, Oscar Y. Shen, Neal C. Chen
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PUBLICATIONS NOT IN THIS THESIS

Expert meeting report: towards a joint European roadmap to address the unmet needs and priorities of paediatric asthma patients on biologic therapy.

Golebski K, Dankelman LHM, Björkander S, Bønnelykke K, Brinkman P, Deschildre A, van Dijk YE, Fleming L, Grigg J, Hamelmann E, Hashimoto S, Kabesch M, Klevebro S, Maitland-van der Zee AH, Merid SK, Nieto A, Niggel J, Nilsson C, Potočnik U, Roberts G, Rusconi F, Saglani S, Valente E, van Drunen C, Wang G, Melén E, Vijverberg SJH.

ERJ Open Res. 2021 Nov 1;7(4):00381-2021. doi: 10.1183/23120541.00381-2021. PMID: 34729368; PMCID: PMC8558470.

Treating severe asthma: Targeting the IL-5 pathway.

Principe S, Porsbjerg C, Bolm Ditlev S, Kjaersgaard Klein D, Golebski K, Dyhre-Petersen N, van Dijk YE, van Bragt JJMH, Dankelman LHM, Dahlen SE, Brightling CE, Vijverberg SJH, Maitland-van der Zee AH.

Clin Exp Allergy. 2021 Aug;51(8):992-1005. doi: 10.1111/cea.13885. Epub 2021 May 21. PMID: 33887082; PMCID: PMC8453879.

Artificial intelligence fracture recognition on computed tomography: review of literature and recommendations.

Dankelman LHM, Schilstra S, IJpma FFA, Doornberg JN, Colaris JW, Verhofstad MHJ, Wijffels MME, Prijs J; Machine Learning Consortium.

Eur J Trauma Emerg Surg. 2023 Apr;49(2):681-691. doi: 10.1007/s00068-022-02128-1. Epub 2022 Oct 26. PMID: 36284017; PMCID: PMC10175338.

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PHD PORTFOLIO

Name PhD student:	Lente H.M. Dankelman
PhD period:	September 2021 – July 2026
Promotors:	Prof. dr. M.H.J. Verhofstad
	Prof dr. J. Doornberg
Co-promotors:	dr. M.M.E. Wijffels
	dr. J.W. Colaris
Erasmus MC Department:	Trauma Research Unit, Department of Surgery

PhD Training	**Year**	**ECTS**
Courses		
Scientific Integrity, Erasmus MC, Rotterdam	2022	0.3
PhD introduction course, Erasmus MC, Rotterdam	2022	0.2
Excel course – Basic	2022	1.0
BioStatistics course R-studio, Massachusetts General Hospital – Harvard Medical school, Boston, USA	2023	2.0
Seminars, workshops, and master classes		
PhD intervision sessions, *Erasmus MC, Rotterdam*	2021-23	0.5
Monthly research and indication meetings, *Massachusetts General Hospital Boston, USA*	2023	0.5
Oral presentations		
Traditional radiography versus computed tomography to assess reduced distal radius fractures. 31st Annual Richard J. Smith Memorial Day, *Massachusetts General Hospital, Boston, USA*	2023	1.0
The prediction of loss of threshold alignment of distal radius fractures: does computer tomography increase accuracy and inter-observer agreement? 31st Annual Richard J. Smith Memorial Day,		

Massachusetts General Hospital, Boston, USA	2023	1.0
Traumadagen, *Amsterdam, The Netherlands*	2023	1.0
Assistentensymposium, *Amsterdam, The Netherlands*	2025	1.0

Association of extrinsic ligament injury with diastasis in scapholunate ligament injury.

Traumadagen, *Amsterdam, The Netherlands*	2023	1.0
EFORT Congress, *Hamburg, Germany*	2024	1.0

Poster presentations

Traditional radiography versus computed tomography to assess reduced distal radius fractures.

Traumadagen, Amsterdam, The Netherlands	2023	1.0
EFORT Congress, *Hamburg, Germany*	2024	1.0

Artificial Intelligence for detection, classification and prediction secondary displacement of distal radius fractures on radiographs; a Systematic review.

EFORT Congress, *Hamburg, Germany*	2024	1.0

The prediction of loss of threshold alignment of distal radius fractures: does computer tomography increase accuracy and inter-observer agreement?

EFORT Congress, *Hamburg, Germany*	2024	1.0

Other attended conferences

IOTA Traumadagen, Amsterdam, The Netherlands	2022	1.0
Chirurgendagen, *The Hague, The Netherlands*	2022	1.0
1st. Annual Harvard Plastic Surgery Day, *Boston, USA*	2023	1.0

Teaching

Supervising bachelor student (thesis)	2023	1.0
Supervising master student (thesis)	2024	2

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Dear colleagues at the Hand, dear **Charlotte, Kevin, Eva, Maximiliaan, Mark, Stella, Oscar, Ingmar, Floris and Rachel**, despite being placed together in a tiny windowless box of a room, with the receptionist loudly calling behind us, we somehow managed not only to produce great research, but also to have a lot of fun and support each other throughout it all. Looking back, that combination of hard work, teamwork, and laughter made that time very special. A special thank you to Charlotte and Kevin. We worked on some amazing projects together! Thank you for your support and your collaboration!

Beste collega's op **Rg-2**, **Saskia**, **Max**, **Miliaan**, **Britt, Niels, Lennard** en alle anderen collega's. Ook al was ik niet vaak op RG-2 te bekennen, als ik na een paar maanden weer eens op kwam dagen, was het altijd gezellig. En gelukkig waren daar altijd nog de Chirurgendagen, Traumadagen of het assistentensymposium, waar we elkaar weer troffen en samen een biertje konden drinken. Sas en Britt in het bijzonder, jullie hebben mij in de eerste maanden echt onder jullie vleugels genomen, waar ik heel dankbaar voor ben.

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Lieve **Vaal**, **Elies**, **Eileen**, **Kiek**, **Jules**, **Tos**, **Noor**, **No** en **Lau**. Vanaf day one waren jullie erbij. Samen met Elies ging ik in 2014 langs bij Mathieu, en daar begon uiteindelijk alles. **Vaalie**, Als weekend kind sliep ik in onze middelbare school tijden bij jouw ouders, toen samen naar Leiden en nu samen dokter en huisgenootjes! We kunnen altijd fijn sparren, en jij brengt een rust met je mee waar ik ontzettend veel van leer. Lieve meiden, jullie hebben mij de afgelopen jaren zoveel rust, gezelligheid en afleiding gegeven, daar ben ik jullie heel dankbaar voor.

Lieve **Bostonians**, lieve **Tom, Jens, Anna U, Anne V, Elaine, Alice, Dylan, Anne P, Lili, Sanne, Huub, Marjolein,** en de rest. Ik zou nog een heel proefschrift kunnen vullen met een dankwoord aan jullie, maar ik moet het toch een 'beetje' kort houden. **Tommie**, de eindeloze dagen samen op de grind in the Teacup, met af en toe een strenge blik en een koptelefoon die ontevreden werd afgezet omdat ik wéér iets wilde vragen, waren mij heel veel waard. Dank voor alles wat ik van je heb geleerd, op academisch vlak én in de keuken. **Jensvader**, spannend vond ik het toen je mij voor het eerst uitnodigde voor tranendal op de Teacup en een goede grind sessie. En nu, vier jaar later, zet jij geen tranendal meer voor mij klaar, maar een glas champagne als mijn geweldige paranimf. Dankjewel, voor alle goede adviezen, over de wetenschap, onze carrière en het leven, en natuurlijk dat je mijn paranimf wilt zijn! En over tettergeintjes gesproken, **Jorkvader**, soms een serieuze blik, vaak onderdeel van de tettergein, maar zelf ook zeker niet vies van een goed tettergein. Dank voor de eindeloze belletjes om advies te geven over mijn vervolgstappen. **Dylie**, ook jij bedank voor alle support en adviezen. Als een wonderkind ben jij aan het doorsjezen, komt die Nature paper nou eindelijk online?? **An**, **E** en **Broek**, oftewel The Fantastic Four, ik wil jullie stuk voor stuk bedanken voor alles wat we in en na Boston hebben beleefd en wat het ons heeft gebracht. Annie met het warme welkom met mij aan de hand mee nemen naar je boys van 106. E, met het eindeloze enthousiasme. En Broekie met je heeerlijke nuchtere blik altijd. Gelukkig wisselde we de research 'af en toe' af met onze tripjes, van Miami en New York tot aan Cadzand. Dank voor al jullie gezelligheid, eindeloze tripjes, borreltjes, en bovenal onze vriendschap! **Lils**, samen hebben wij dagen en dagen doorgebracht in dat 2x2-hokje op de Hand. We konden samen sparren over onderzoek, maar vooral ook lekker keten met de boys en Sanne op 106. En Sanne, wees nou eerlijk, het beste onderzoek wordt toch gewoon in Miami geschreven? Lieve Majro, An, Huub en iedereen die mijn tijd daar zo bijzonder heeft gemaakt en echt heeft bijgedragen aan dit proefschrift, heel veel dank voor alles!
En vergeet niet mensen: "*Work hard, Play hard*".

Lieve strengste, maar liefste tante, lieve **Epp**. We kunnen er lang of kort over doen, maar als jij mij in 2014 niet naar het Erasmus MC had gestuurd voor een meeloop dag met dr. Wijffels, en zes jaar later niet had gezegd: 'Lent, bel Mathieu anders een keertje op,' dan hadden we nu niet gestaan waar we vandaag staan en had ik dit dankwoord nooit kunnen schrijven. Ik wil je ontzettend bedanken voor alles wat je voor mij hebt gedaan, de eerste zet in dit promotie traject. Helaas was mijn eerste dag, jouw laatste… Maar gelukkig zitten we elk jaar samen bij het kerstdiner! Super bedankt Tant voor alles wat je hebt gedaan en dat je in me hebt geloofd!

Lieve **Jaapie**, Jij kwam iets later in dit traject. Met je felblonde haren zat je daar te wachten in Café de Pels, terwijl ik de volgende dag doodleuk zei dat ik even een dag 'ogen ging lepelen'. Ik kan me voorstellen dat je toen ook niet helemaal wist waar je in terecht was gekomen. Ondanks dat het allemaal nieuw voor je was, dat je meestal niet verder kwam dan de titel van mijn papers en meermaals vroeg hoe het met mijn 'werkstuk' of 'scriptie' ging, ben je in de laatste fase, en nog steeds, een enorme steun voor mij. Dank dat ik gewoon mezelf kan zijn en met twee potten nutella en een stabel bouwtekeningen aan de keukentafel kan gaan zitten. Jij maakt het leven nóg leuker en vrolijker en je maakt mij super gelukkig. I love you!

Lieve familie,
Zonder jullie was dit proefschrift nooit geworden tot wat het nu is. Jullie steun, betrokkenheid en geloof hebben in de afgelopen jaren ontzettend veel voor mij betekend. Lieve **Brecht**, mijn grote sus, ik kijk al mijn hele leven tegen je op. Zoals ik altijd kan zeggen: 'ik wil dat ook', is dat eigenlijk nooit veranderd. Je bent iemand aan wie ik heel veel heb en op wie ik altijd kan bouwen. Ik vind het bijzonder hoe je alles doet en alle balletje hooghoudt. Hoe jij zo trots kan zijn op mij, ben ik dat ook op jou! Ik vind het dan ook extra bijzonder dat jij mijn paranimf wilt zijn op deze speciale dag, hopelijk mag ik dan uiteindelijk de rozenblaadjes naar je gooien! Ik had mij echt geen betere kunnen wensen. Lieve **Flippie**, Ook jou wil ik heel erg bedanken voor al je steun. Van vroeger vechten naar het beste Lego blokje in de bak, samen boomhutten bouwen en ik die niet mee mocht gamen, naar samen een super vet bouwproject doen,

dinertjes koken met te veel bieren drinken en nu ook onze eigen 'bakkerij'. Misschien begreep je niet meer dan dat mijn proefschrift over iets met een pols ging, maar dat maakte voor jouw enthousiasme en trots helemaal niets uit.

Lieve **pap**, jij, als uitgeloot paramedicus en tevens tangensman, hebt ook zeker je steentje bijgedragen aan dit proefschrift. Jij bent mijn allergrootste supporter, zowel op academisch gebied, ook al was je niet volledig thuis in medisch onderzoek, als daarbuiten. Zelfs jij wist de spelfouten bij de ingewikkelde volaire ligamenten eruit te halen, terwijl het waarschijnlijk vooral Chinees voor je was. Jij wist de laatste puntjes op de I te zetten met de layout van dit meesterwerk. Ik vind het zo fijn dat ik altijd met alles bij je terrecht kan, meestal ver ver buiten de scope van dit proefschrift. Ik wil je heel erg bedanken voor alle steun van de afgelopen jaren en dat jullie mij altijd hebben aangemoedigd om mijn eigen pad te kiezen en mijn dromen achterna te gaan. En dankzij jou vergeet ik nooit: '*kan niet, bestaat niet*'. En dan kan ik denk ik de belangrijkste persoon, die denk ik het meest heeft bijgedragen aan dit proefschrift, niet vergeten: Lieve **mam**, als er iemand is die elke letter van dit proefschrift voorbij heeft zien komen en heeft verbeterd, dan ben jij het wel. Jij was mijn promotor, co-promotor, spellingscontroleur en mentor in één. Zonder jou was dit proefschrift nooit geworden tot wat het nu is. Ik heb mij vaak afgevraagd hoe anderen dit doen zonder een moeder die alles woord voor woord meeleest en mee denkt? Je bent echt een voorbeeld voor mij en ik kijk ontzettend naar je op. Ik wil je ontzettend bedanken voor alle hulp, goede adviezen en alle tijd die je in dit proefschrift hebt gestoken. Daarnaast ben je natuurlijk ook nog gewoon mijn liefste moeder, die ook naast dit proefschrift altijd voor me klaar staat, waar ik altijd terecht kan en die mij de beste adviezen kan geven. Lieve pap en mam, woorden schieten bijna tekort: dank voor alle steun de afgelopen jaren en alle liefde die jullie geven.

Heel veel liefs,
Lente Dankelman

APPENDICES

LETTER TO THE AUTHOR

Dear young Lente,

In the spring of 1999, you were born into the most caring and loving family, , among the cows and sheep in the small town called Nigtevecht, the Netherlands. I want to tell you a little about what the future holds for you. But first, please be careful building all those tree houses with your big brother. You will one day find out that broken bones do heal, but for now: casts are the worst. I know your dream is to become a carpenter but keep your eyes open! At 14, you will meet dr. Mathieu Wijffels, a trauma surgeon at Erasmus Medical Center in Rotterdam. That meeting will shift your dream from becoming a carpenter to becoming a trauma surgeon. The next step? Studying medicine. But first, you will learn how to be on your own in a small town in Ghana, where you will catch your first glimpse of healthcare in a resource-limited setting.

After graduating from Sint-Vitus College in Bussum in 2017, your path will take a slightly different turn. You will start with the bachelor program Bio-Pharmaceutical Sciences at Leiden University, following in your mother's footsteps. However, your father taught you: 'Kan niet, bestaat niet!'. After one year you will be admitted to Medical School of the University of Amsterdam in 2018. Congratulations! You are still a girl who is always on the move. Eager to gain hands-on experience, you will start working at Weefsel Uitname Organizatie Nederland (WUON) as a bone, tendon, and heart tissue retrieval technician. In this role, you will be responsible for tissue procurement from deceased donors and serve as the medical lead of a team that includes fellow medical students. You are growing up…

As time goes on, you will become more serious about your ambitions and often think back to that formative internship in 2014. After completing your bachelor's degree in Medicine, in September 2021 you will return to dr. Wijffels at the Trauma Research Department of the Erasmus Medical Center to drink a good cup of coffee. There, you will be given the opportunity to start as a PhD candidate focusing on distal radius fractures, under the supervision of Prof. dr. Verhofstad, dr. Wijffels, and dr. Colaris later joined by Prof. dr. Doornberg from University Medical Center Groningen. From January to September 2023, eager to explore research beyond national borders, you will continue your research at Massachusetts General Hospital in Boston, USA, under the supervision of Dr. Chen. There, you will broaden the scope of your PhD to include scapholunate ligament injuries. Still with me? After returning to the Netherlands in October 2023, you will begin your clinical rotations for Master of Medicine alongside your PhD.

Now, Lente, 12 years later, I have just started as a resident not in training at the Department of Surgery at Dijklander Hospital in the Netherlands. Your ambition has remained unchanged; you still want to become a trauma surgeon. I am very excited what the future holds for you!

I hope to write to you again soon.

Kind regards,
Lente Dankelman