Wrist motion!?

Michelle Esther Brinkhorst

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CHAPTER 1

General introduction

The wrist is a complex joint with multiple carpal bones and ligaments which form a delicate balance. There is a high potential for osteoarthritis, due to ligament injuries or fractures. Early diagnosis of carpal fractures and ligament injuries may prevent the development of osteoarthritis.

Stiffness and pain are the most common symptoms of osteoarthritis. One or more joints in the body can be affected, but when it occurs in the wrist, it may obstruct simple activities of daily living and eventually result in severe functional impairments. Treatment is therefore based on alleviating pain, preventing progression and preserving wrist motion.

Inappropriate evaluation, management and/or treatment of wrist injuries may result in a reduced quality of life, long-term disability and even loss of work.[1] Approximately 920.000 patients visit the emergency department each year in the Netherlands. Around 56.000 of these patients are people of working age (20-64 years) with hand or wrist injuries, which accounted for 379 million euro's per year in health-care costs in 2012.[2] Productivity costs as a result of work absenteeism were 75% (284 million euro's), which are generally higher than health-care costs.[2, 3]

Understanding the anatomy and biomechanics of the wrist is crucial for diagnosing and treating wrist osteoarthritis. In this introduction, we will start with discussing the basic anatomy of the wrist and carpal kinematics, followed by explaining the pathomechanism of wrist osteoarthritis, current diagnostic options, and different motion-preserving treatment options. Finally, the aim and outline of this thesis is provided.

Anatomy

The wrist consists of the distal radius, distal ulna, the carpal bones and the proximal part of the metacarpals. The multi-articulated architecture of the wrist allows a wide range of motion (flexion-extension, radial-ulnar deviation and circumduction). There are eight carpal bones, which are organized in two rows (Figure 1).

The scaphoid, lunate, triquetrum and pisiform form the proximal carpal row, which articulates with the distal radius and ulna. The trapezium, trapezoid, capitate and the hamate comprise the distal carpal row. Ligaments in the wrist can be divided into extrinsic and intrinsic ligaments. The extrinsic carpal ligaments connect the carpal bones with the radius, ulna and metacarpals. The intrinsic carpal ligaments form an interconnection between the carpal bones.

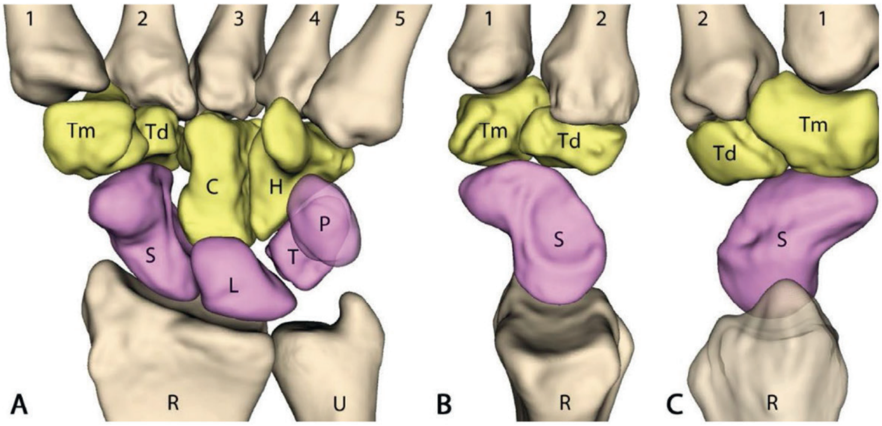

Figure 1 ***A**: Palmar view,* ***B**: ulnar view, and* ***C:** radial view of a 3D model of the wrist including the proximal row (purple bones) and distal row (yellow bones).*
Tm: trapezium; Td: trapezoid; C: capitate; H: hamate; S: scaphoid; L: lunate; T: triquetrum; P: pisiform; R; radius; U: Ulna; 1-5: metacarpal bones. Reproduced from thesis P.W.L. ten Berge (Characterizing scaphoid non-union deformity using 2-D and 3-D imaging techniques)

Motion and stability of the wrist is achieved through the articulation and shape of the carpal bones, constraints by soft-tissue (such as ligaments) and load produced by the muscles from the forearm, which are attached to the bases of the metacarpals. Cartilage reduces friction between joints and functions as a shock absorber. The range of motion of the uninjured wrist is approximately 80° flexion, 70° extension, 15 – 20° in radial deviation and 30 – 35° ulnar deviation. The wrist joint can be divided into the radiocarpal joint (which is formed by the distal radius which articulates with the scaphoid and lunate) and the midcarpal joint (which is formed by the proximal surface of distal carpal row which articulates with the distal part of the proximal carpal row).

Carpal kinematics

Carpal motion is complex with multiple axes and rotations around these axes during different motions of the wrist. Three primary axes can be distinguished; with motion in all planes: flexion-extension in the sagittal plane, radial-ulnar deviation in the coronal plane and pronation-supination in the transverse plane. Both proximal and distal carpal rows have different carpal kinematics.

There are no tendons attached to the proximal or distal carpal row, so movement is initiated by load and motion of adjacent bones. The distal carpal row forms a relative “fixed unit” with the second and third metacarpal. The proximal row acts as an intercalated segment between the distal carpal row and the bones of the forearm.[4] Movement of the proximal carpal row is initiated by load and motion of the distal carpal row.[5] When the wrist is flexed or extended, both the proximal and distal carpal row flex or extend, respectively. During radial deviation of the wrist, the proximal row flexes and during ulnar deviation, it extends.[6] During axial compression, the scaphoid will flex as a result of its shape and position. On the ulnar side of the wrist, axial compression moves the triquetrum in extension as a result of the shape of the triquetrum-hamate joint surface. The lunate, which is positioned in-between the scaphoid and triquetrum, is in a balanced position due to the combined effect of the opposing forces from both sides which are directed via the scapho-lunate (SL) and lunotriquetral (LT) intrinsic ligaments.

In vivo, carpal bones are believed to follow a much more complex motion than the traditionally defined axes in the anatomic planes. The term "*dart throwing motion"* has been proposed by investigators to describe this motion that is mostly used during activities of daily living. It involves an arc of motion of the wrist from radial deviation with the wrist extended to ulnar deviation with the wrist flexed.[7-9] During dart throwing motion there is almost no motion of the lunate, but motion mostly occurs through the midcarpal joint.[10] Throughout this plane of motion, it is believed that there is more stability, which allows consistent power grip during wrist motion.

Overall, carpal kinematics are dependent on the position of the wrist during load, motion of the wrist, morphology of the carpal bones, orientation of the articulating surfaces, the direction of transferred forces and ligament constrains. The proximal row has a tendency to undergo mechanical collapse when there is an interruption within the ligamentous or bony segments.

Development of posttraumatic wrist osteoarthritis

In clinical practice, osteoarthritis of the wrist is one of the most common conditions seen by hand surgeons.[11] Ninety-five percent of all degenerative changes of the wrist are related to the scaphoid.[12, 13] Wrist osteoarthritis can be roughly divided into primary or secondary osteoarthritis. Primary osteoarthritis is more rare and can be a result of idiopathic carpal avascular necrosis [Kienböck's (lunatomalacia) or Preiser's (scaphoid) disease] and congenital wrist abnormalities like Madelungs's deformity.[12, 14-17] Post-traumatic (=secondary osteoarthritis) causes, such as scaphoid non-union advanced collapse (SNAC), scapholunate advanced collapse (SLAC) and osteoarthritis secondary to an intra-articular fracture of the distal radius or ulna, are commonly seen. SLAC is most common today of all the cases of wrist osteoarthritis (72%) [12, 18], followed by the SNAC wrist.[19]

Sometimes, no detectable cause is found for wrist osteoarthritis, for instance in some cases of scapho-trapezio-trapezoid osteoarthritis.[11]

Pathomechanism

Carpal instability, which is defined as an inability to bear physiological load with malalignment of the carpal bones, is caused by disruption of an intercarpal ligament or fracture of a carpal bone.[20] Various patterns of carpal instability have been described.[21] Carpal instability dissociative (CID) is seen when there is a rupture of the ligament between two carpal bones in the same row. Carpal instability non-dissociative (CIND) is seen when there is a rupture of the ligament between the carpal bones of the proximal and distal carpal row. For example, with an external force such as a force due to a fall on an outstretched hand. The scaphoid will be in a progressive extension as a result, transmitting this tension to the lunate via the scapholunate (SL) ligament. Due to this tension the SL ligament may rupture, which can over time lead to complete scapholunate dissociation (SLD).

When the SL ligament is ruptured or there is a long-standing scaphoid non-union, the proximal row collapses into an abnormal posture. The scaphoid flexes and the lunate will extend which can be seen on the lateral views of plain radiographs and is known as dorsal intercalated segment instability (DISI).[22]

In SLAC wrists the hyperflexed scaphoid results in cartilage degeneration at the distal radius and the proximal part of the scaphoid. In SNAC wrists the SL ligament is preserved and the degenerative changes will primarily effect the scaphocapitate joint. There is a close similarity in progression of joint degeneration between the SLAC and SNAC wrist. In this thesis we will concentrate on the proximal row and the development of osteoarthritis as a result of scaphoid fracture or SL ligament rupture.

Stages of SNAC and SLAC wrists

Watson and Ballet evaluated over 200 radiographs of the wrist and classified the severity of degenerative changes in patients with SLAC wrists into three stages (Figure 2).[12, 13]

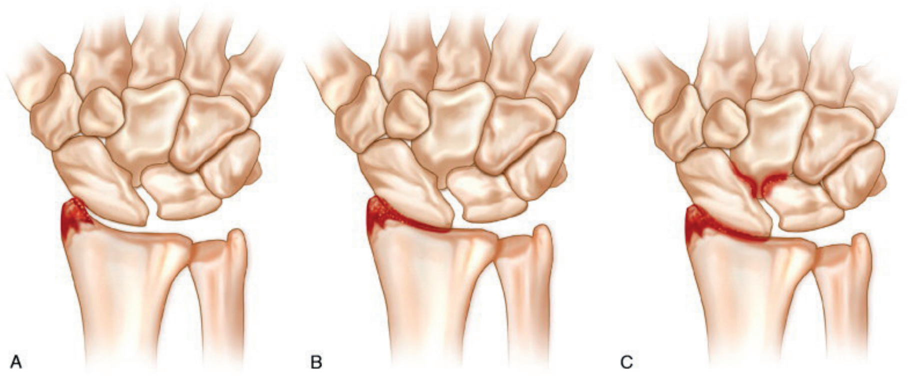

Figure 2 *Progressive arthritic changes in SLAC osteoarthritis.* ***A****: Stage 1, arthritis of the radial styloid and styloscaphoid region.* ***B****: Stage 2, progression of arthritis towards the radioscaphoid joint.* ***C****: Stage 3, progression of arthritis with involvement of the capitolunate joint. Reprint with permission from A. Chhabra and J. Isaacs (Arthritis and Arthroplasty: The Hand, Wrist and Elbow) Elsevier*

Development of wrist osteoarthritis in patients with SNAC wrists has some subtle differences compared to SLAC wrists.[23, 24] Since the SL ligament is still intact, the degenerative pattern progresses to the midcarpal joint and the proximal radioscaphoid joint is preserved (Figure 4). Eventually SNAC and SLAC wrists may lead to a fourth stage: pancarpal osteoarthritis, in which the radiolunate joint is also involved.[11, 17, 25-27]

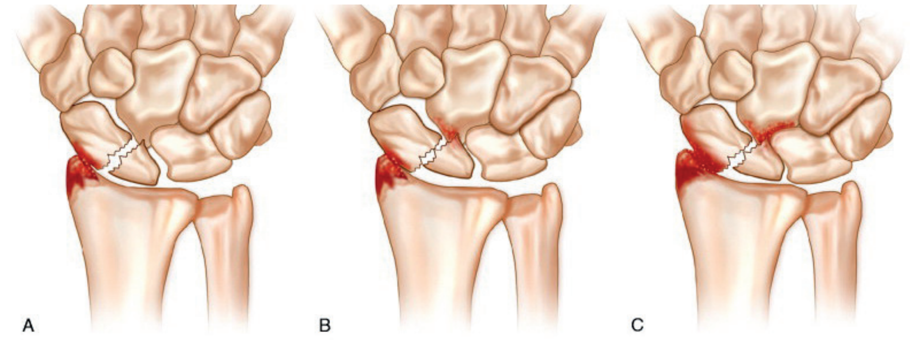

Figure 3 *Progressive arthritic changes in SNAC osteoarthritis.* ***A:*** *Stage 1, arthritis of the radial styloid and styloscaphoid region.* ***B:*** *Stage 2, progression of arthritis towards the proximal scaphocapitate joint.* ***C:*** *Stage 3, progression of arthritis with ivolvement of the capitolunate joint. Reprint with permission from A. Chhabra and J. Isaacs (Arthritis and Arthroplasty: The Hand, Wrist and Elbow) Elsevier*

Imaging tools for diagnosis of wrist joint problems

Diagnosing carpal instabilities as early as possible is crucial for adequate treatment to prevent further cartilage degeneration. Thorough history and physical examination is followed by a radiological assessment. Several diagnostic options are available. Plain radiographs will give a quick skeletal overview which is ideal for diagnosing fractures and dislocations. However, carpal instabilities, ligament ruptures and cartilage degeneration are difficult to diagnose due to inconsistent measurement methods and a wide reference ranges. Plain or stress radiographs, like the clenched fist view, were proposed to reveal osseous diastasis.[28] Although it is a commonly used imaging tool, there is no strong evidence available on accuracy in the detection of ligamentous tears (sensitivity 57%, specificity 94%).[29] Magnetic resonance imaging (MRI) is sometimes used to identify ligamentous tears when plain radiographs are normal or inconclusive; it, however, has a sensitivity of only 11% and specificity of 30%.[30, 31] The newer 3.0 tesla MRI is more sensitive (70%-81%) and very specific (100%) for detecting SL ligament injury. However, it does not have an additional value in patients with a high clinical suspicion of SL rupture.[32] Radiographs and MRI scans are both static modalities and may therefore lack specificity for diagnosing carpal instabilities.[28, 30] Fluoroscopy allows a dynamic assessment of the wrist. However, the 2D nature of this method limits it to diagnose complex pathologies like carpal instabilities.[33] Computed tomography (CT) produces three-dimensional images and has been widely used to diagnose complex pathologies and dislocations. It can be used as a static modality; however, recently, four-dimensional CT (3D+time) was introduced which allows evaluation of carpal kinematics during wrist motion.[34, 35] Studies in this thesis will investigate this technique more thoroughly.

Treatment of posttraumatic wrist osteoarthritis

Historically, most posttraumatic wrist osteoarthritis pathologies were treated with total arthrodesis, which would eliminate all movement between radiocarpal and ulnocarpal joints.[36, 37] Nowadays, treatment of wrist osteoarthritis starts with conservative treatment like a splint/cast immobilization, non-steroidal anti-inflammatory medications and even intra corticosteroid-articular injections. However, the disease is more advanced in most patients so the conservative options may be insufficient as time goes on. Commonly, the goal of surgery is to eliminate pain, stop or minimise progression of arthritis, and preserve as much motion as possible. There are different motion-preserving surgical options for the four different stages of posttraumatic wrist osteoarthritis. Specific treatment for each patient is based on the patient's symptoms, expectations, stage of the disease, and functional demands.

Wrist denervation is performed to eliminate pain and can therefore be performed at any stage. Furthermore, different types of pyrocarbon implants have been suggested, such as the Adaptive Proximal Scaphoid Implant, the Scaphoid Trapezium Interposition Implant and the Amandys® (replaces the lunate, proximal two-thirds of the scaphoid and part of the head of the capitate). Long-term results of these implants are still needed.

In stage I SNAC or SLAC wrists, radial styloidectomy, possibly combined with excision of the distal scaphoid in SNAC wrists, is one of the simplest options. However, reconstructive methods are also still possible. Scaphoid reconstruction with a bone block, screw or plate fixation are commonly used in combination with resection of the radial styloid in a SNAC wrist. SL ligament reconstruction or limited carpal fusion in combination with resection of the radial styloid are therapies of choice for a stage I SLAC wrist.

Controversy exists regarding the treatment of stage II SNAC or SLAC wrists.[11] There are two commonly used motion-preserving reconstructive options: four-corner fusion (FCF) and proximal row carpectomy (PRC). In PRC patients, all carpal bones of the proximal row are removed. This removal changes the joint biomechanically by the creation of a new non-physiological joint (Figure 4A). In FCF patients, the range of motion of the wrist comes from the radiocarpal joint, so the flexion-extension of the wrist stays physiological, but the radial-ulnar deviation is non-physiological (Figure 4B). Mulford et al. performed a meta-analysis comparing case-series which showed no significant differences for strength, pain relief, or subjective outcomes.[38] Zhu et al.[39] studied these changes in cadavers and found that the mismatch of the radiocapitate articulation was caused mainly by the contour of the proximal capitate. There is a reduction in contact area, so the PRC produces a “hinge-and-roll” motion instead of a “ball-and-socket” motion at the radiocarpal joint.[40]

In case of degeneration of the capitate head, as in Stage III of the SNAC or SLAC wrist, proximal row carpectomy can still be performed, but interposition of a capsular flap between the capitate head and the lunate fossa is necessary. Alternatively, intercarpal fusion such as four-corner fusion or lunocapitatie arthrodesis are commonly performed procedures. Less common is a cap prosthesis in PRC for the proximal capitate to replace the damaged proximal pole.

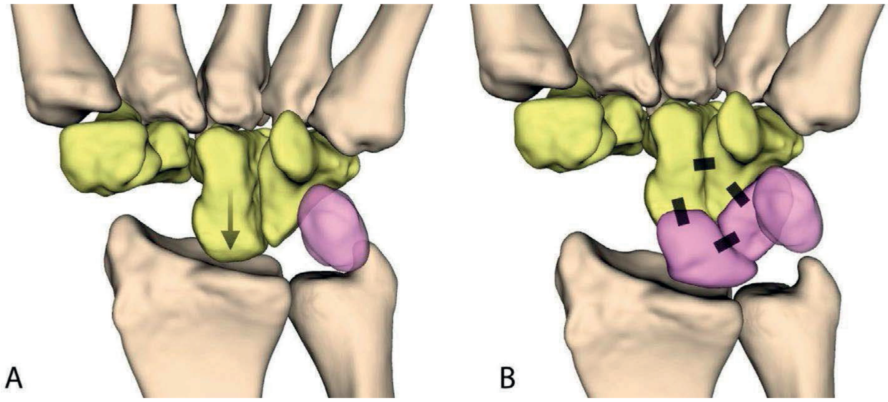

Figure 4 *Palmar view of a 3D model of the wrist after* ***A****: Proximal row carpectomy (PRC),* ***B****: Four-corner fusion (FCF) Reproduced from thesis P.W.L. ten Berge (Characterizing scaphoid non-union deformity using 2-D and 3-D imaging techniques)*

In stage IV of the SNAC or SLAC wrist, total wrist implant is an attractive motion-preserving surgical alternative. Depending on age, profession, hand dominance and co-morbidities in this stage also wrist arthrodesis can be performed.

Aims and outline of this thesis

The overall aim of our research project was to prevent the further development of wrist osteoarthritis by improving early diagnostics and treatment for patients with posttraumatic wrist osteoarthritis. We started by studying the clinical results after several motion-preserving surgical techniques to understand the effect and burden patients encounter after surgery (**specific aim part 1)**. There is still much discussion about which motion-preserving technique is best for patients with stage 2 SNAC and SLAC wrist. Therefore, we started by studying dynamic effects and effects on daily living after PRC and FCF. For end stage wrist osteoarthritis, two options are available: immobilisation by total wrist fusion or motion-preserving by implanting a prosthesis. Although many wrist prostheses are available not much is known about the results of the latest generation wrist prostheses in posttraumatic wrists. We aimed to provide a better understanding of results and wrist dynamics after several motion-preserving treatments.

After studying the results after these motion-preserving techniques, our aim was to improve the understanding of in vivo carpal kinematics (**specific aim part 2**). Better understanding of wrist biomechanics will aid in earlier diagnostics of complex wrist injuries, choosing between different treatment options, developing different surgical options, and may help in the design of the next generation of wrist prostheses.

REFERENCES

1. Gustafsson, M. and G. Ahlstrom, Problems experienced during the first year of an acute traumatic hand injury - a prospective study. J Clin Nurs, 2004. 13(8): p. 986-95.
2. de Putter, C.E., et al., Healthcare costs and productivity costs of hand and wrist injuries by external cause: A population-based study in working-age adults in the period 2008-2012. Injury, 2016. 47(7): p. 1478-82.
3. Nilsen, P., D. Hudson, and K. Lindqvist, Economic analysis of injury prevention--applying results and methodologies from cost-of-injury studies. Int J Inj Contr Saf Promot, 2006. 13(1): p. 7-13.
4. Kauer, J.M., The mechanism of the carpal joint. Clin Orthop Relat Res, 1986(202): p. 16-26.
5. Foumani, M., et al., The effect of tendon loading on in-vitro carpal kinematics of the wrist joint. J Biomech, 2010. 43(9): p. 1799-805.
6. Foumani, M., et al., In-vivo three-dimensional carpal bone kinematics during flexion-extension and radio-ulnar deviation of the wrist: Dynamic motion versus step-wise static wrist positions. J Biomech, 2009. 42(16): p. 2664-71.
7. Crisco, J.J., et al., In vivo radiocarpal kinematics and the dart thrower's motion. J Bone Joint Surg Am, 2005. 87(12): p. 2729-40.
8. Werner, F.W., et al., Scaphoid and lunate motion during a wrist dart throw motion. J Hand Surg Am, 2004. 29(3): p. 418-22.
9. Wolfe, S.W., et al., The dart-throwing motion of the wrist: is it unique to humans? J Hand Surg Am, 2006. 31(9): p. 1429-37.
10. Crisco, J.J., et al., The mechanical axes of the wrist are oriented obliquely to the anatomical axes. J Bone Joint Surg Am, 2011. 93(2): p. 169-77.
11. Weiss, K.E. and C.M. Rodner, Osteoarthritis of the wrist. J Hand Surg Am, 2007. 32(5): p. 725-46.
12. Watson, H.K. and F.L. Ballet, The SLAC wrist: scapholunate advanced collapse pattern of degenerative arthritis. J Hand Surg Am, 1984. 9(3): p. 358-65.
13. Watson, H.K. and J. Ryu, Evolution of arthritis of the wrist. Clin Orthop Relat Res, 1986(202): p. 57-67.
14. Luo, J. and E. Diao, Kienbock's disease: an approach to treatment. Hand Clin, 2006. 22(4): p. 465-73; abstract vi.
15. Lauder, A.J. and T.E. Trumble, Idiopathic avascular necrosis of the scaphoid: Preiser's disease. Hand Clin, 2006. 22(4): p. 475-84; abstract vi.
16. Arora, A.S. and K.C. Chung, Otto W. Madelung and the recognition of Madelung's deformity. J Hand Surg Am, 2006. 31(2): p. 177-82.
17. Krimmer, H., et al., [Post-traumatic carpal collapse (SLAC- and SNAC-wrist)--stage classification and therapeutic possibilities]. Handchir Mikrochir Plast Chir, 1997. 29(5): p. 228-33.
18. Watson, H.K., J. Weinzweig, and J. Zeppieri, The natural progression of scaphoid instability. Hand Clin, 1997. 13(1): p. 39-49.

19. Sauerbier, M., et al., [Surgical treatment possibilities of advanced carpal collapse (SNAC/SLAC wrist)]. Unfallchirurg, 2000. 103(7): p. 564-71.

20. Garcia-Elias, M., The treatment of wrist instability. J Bone Joint Surg Br, 1997. 79(4): p. 684-90.

21. Larsen, C.F., et al., Analysis of carpal instability: I. Description of the scheme. J Hand Surg Am, 1995. 20(5): p. 757-64.

22. Linscheid, R.L., et al., Traumatic instability of the wrist: diagnosis, classification, and pathomechanics. J Bone Joint Surg Am, 2002. 84-A(1): p. 142.

23. Vender, M.I., et al., Degenerative change in symptomatic scaphoid nonunion. J Hand Surg Am, 1987. 12(4): p. 514-9.

24. Inoue, G. and M. Sakuma, The natural history of scaphoid non-union. Radiographical and clinical analysis in 102 cases. Arch Orthop Trauma Surg, 1996. 115(1): p. 1-4.

25. Krimmer, H. and U. Lanz, [Post-traumatic carpal collapse. Follow-up and therapeutic concept]. Unfallchirurg, 2000. 103(4): p. 260-6.

26. Weinzweig, J. and H.K. Watson, Limited wrist arthrodesis, in The Wrist, J. Weinzweig and H.K. Watson, Editors. 2001, Lippincott Williams & Wilkins: Philidelphia. p. 521-543

27. Alnot, J.Y., C. Apredoaei, and B. Frot, Resection of the proximal row of the carpus. A review of 45 cases. Int Orthop, 1997. 21(3): p. 145-50.

28. Patel, R.M., et al., Comparisons of three radiographic views in assessing for scapholunate instability. Hand (N Y), 2015. 10(2): p. 233-8.

29. Pliefke, J., et al., Diagnostic accuracy of plain radiographs and cineradiography in diagnosing traumatic scapholunate dissociation. Skeletal Radiol, 2008. 37(2): p. 139-45.

30. Zanetti, M., J. Bram, and J. Hodler, Triangular fibrocartilage and intercarpal ligaments of the wrist: does MR arthrography improve standard MRI? J Magn Reson Imaging, 1997. 7(3): p. 590-4.

31. Morley, J., J. Bidwell, and M. Bransby-Zachary, A comparison of the findings of wrist arthroscopy and magnetic resonance imaging in the investigation of wrist pain. J Hand Surg Br, 2001. 26(6): p. 544-6.

32. Spaans, A.J., et al., The value of 3.0-tesla MRI in diagnosing scapholunate ligament injury. J Wrist Surg, 2013. 2(1): p. 69-72.

33. Sulkers, G.S., et al., The diagnostic accuracy of wrist cineradiography in diagnosing scapholunate dissociation. J Hand Surg Eur Vol, 2014. 39(3): p. 263-71.

34. Athlani, L., et al., Assessment of scapholunate instability with dynamic computed tomography. J Hand Surg Eur Vol, 2020. 45(4): p. 375-382.

35. Rauch, A., et al., Four-dimensional CT Analysis of Wrist Kinematics during Radioulnar Deviation. Radiology, 2018. 289(3): p. 750-758.

36. Clayton, M.L. and D.C. Ferlic, Arthrodesis of the arthritic wrist. Clin Orthop Relat Res, 1984(187): p. 89-93.

37. Weiss, A.P. and H. Hastings, 2nd, Wrist arthrodesis for traumatic conditions: a study of plate and local bone graft application. J Hand Surg Am, 1995. 20(1): p. 50-6.

38. Mulford, J.S., et al., Proximal row carpectomy vs four corner fusion for scapholunate (Slac) or scaphoid nonunion advanced collapse (Snac) wrists: a systematic review of outcomes. J Hand Surg Eur Vol, 2009. 34(2): p. 256-63.

39. Zhu, Y.L., et al., Biomechanics of the wrist after proximal row carpectomy in cadavers. J Hand Surg Eur Vol. 35(1): p. 43-5.

40. Imbriglia, J.E., et al., Proximal row carpectomy: clinical evaluation. J Hand Surg Am, 1990. 15(3): p. 426-30.

PART I

Results after motion-preserving surgery in SNAC and SLAC wrists

CHAPTER 2

Dynamic assessment of wrist after proximal row carpectomy and four-corner fusion

H.P. Singh, **M.E. Brinkhorst**, J.J. Dias, T.M. Moojen, S.E.R. Hovius, B. Bhowal

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ABSTRACT

Purpose: To investigate the effect of 4-corner fusion (FCF) or proximal row carpectomy (PRC) on wrist motion, strength, and outcome for 2 different cohorts from 2 separate institutions performing either FCF or PRC for stage 2/3 scaphoid nonunion advanced collapse and scapholunate advanced collapse.

Methods: We assessed 46 subjects (24 FCF and 22 PRC), mean age 54 years, with a flexible electrogoniometer to measure maximum wrist motion and circumduction and compare it with the nonsurgical wrist. We analyzed the shape, size, rate, and smoothness of the circumduction curves. We assessed the maximum grip and sustainability of grip for 60 seconds using a digital grip analyzer. Patient evaluation measure and Michigan Hand Questionnaires measured patient-reported outcomes.

Results: Flexion-extension in the surgically treated wrist was 50% of the nonsurgical side after a FCF and 65% after a PRC. The radioulnar deviation component in circumduction of the surgically treated wrist was similar but markedly decreased after either procedure. The mean area of circumduction of the surgically treated wrist was similar after a PRC and a FCF but was 30% of the nonsurgical wrist. The center of the circumduction ellipse after a PRC was closer than after a FCF to the opposite wrist. The orientation of the plane of circumduction was 22° to the vertical flexion-extension plane after a PRC. After a FCF, the plane was more vertical (9°). The peak grip strength and the area under the force time curve was 80% of the nonsurgical side after a PRC and 60% after a FCF. The Michigan Hand Questionnaire result was 90% of the score for the nonsurgical hand after a PRC and 75% of score for the nonsurgical hand after a FCF.

Conclusions: The PRC provided improved flexion-extension with a circumduction curve concentric with the nonsurgical wrist. The FCF limited extension and ulnar deviation more than did a PRC.

INTRODUCTION

Management of osteoarthritis associated with scaphoid nonunion (SNAC) [1] or scapholunate advanced collapse (SLAC) [2] remains a challenge. The 2 preferred surgical options are scaphoid excision with 4-corner fusion (FCF) and proximal row carpectomy (PRC). However, the impact of these 2 procedures remains unclear.[3,4] Grip strength is greater after a FCF but it carries a higher risk of nonunion or complications resulting from hardware.[5] The range of motion may be greater after a PRC but the durability of this movement is unknown and may deteriorate owing to progression of radiocarpal arthritis.[6]

Previous case series [3,7] and systematic reviews [4] studied static wrist motion after the 2 operations. Peak grip strength is routinely used to measure hand strength but it provides an incomplete picture of the ability of the hand.[8] Uniplanar range of motion measurements may not accurately represent the total capacity [9], velocity, and smoothness of the functional motion path of the wrist after surgery.

We studied 2 different cohorts of PRC and FCF for stage 2 and 3 SNAC and SLAC wrists from 2 separate institutions. Kinematic assessment of the wrist with flexible biaxial electrogoniometry to measure circumduction, force time curves [10] to measure grip strength, and patient-reported outcome questionnaires were compared and correlated with the nonsurgical side.

MATERIALS AND METHODS

Two centers were involved in the study because it was difficult to recruit sufficient numbers of FCF and PRC cases at one center owing to limited numbers of stage 2/3 SLAC and SNAC wrists. We identified a center in The Netherlands with a similar patient profile to the center in the United Kingdom (UK) where the research was initiated. The research question for this study was to document how the wrist performed after either of the 2 operations. A randomized trial would require a sufficiently long follow-up to discern differences in function after FCF or PRC.[6,11] A cross-sectional clinical outcomes study was therefore considered appropriate.

Two independent researchers not involved in the treatment of the patients assessed all patients in special review clinics. The main source of variation between observers using electrogoniometry was the site of application of the goniometer on the volunteer's forearm.[12,13] A standard protocol of assessment and application of the electrogoniometer was agreed upon and this was closely reviewed for consistency by another independent researcher.

We identified 107 patients who had a FCF or a PRC at either center. We included patients who had surgery for stage 2/3 SNAC or SLAC wrist; were older than 18 years; had only one major surgical procedure on the wrist, either PRC or FCF; had had surgery more than 6 months previously; and had the ability to give consent. Patients with rheumatoid arthritis, multiple operations on the same wrist or hand, major surgical procedure(s) or pathology on the opposite wrist, and learning disabilities or other neuromuscular pathology of upper extremities were excluded from the study.

Forty-eight patients had a FCF in a tertiary care hospital in the UK from 1999 to 2011. Five were excluded. Twenty-four patients agreed to attend the research clinic and were assessed (Figure 1). A total of 59 patients had a PRC in another specialist hospital in The Netherlands from 2006 to 2010; 15 were excluded. Twenty-four patients agreed to attend research clinics but 2 were too ill to attend. Excluded patients were similar demographically to the patients included in the study. The hospital records were reviewed to compare age, hand dominance, sex distribution, and side of surgery. We obtained ethical committee approval from both institutions. We contacted all the patients by mail, inviting them to attend research clinics.

Both procedures were performed using described techniques. The FCF for SLAC/SNAC stage 2 or 3 was done through a longitudinal dorsal incision with a ligament-splitting approach to the joint. The posterior interosseous nerve was divided proximal to the joint. After confirming that the cartilage over the lunate and the lunate fossa of the radius was intact, the scaphoid was excised and the cartilaginous sur- face between the 4 carpals was removed. The dorsal intercalated segment instability deformity was corrected and maintained temporarily with K-wires while a bed was created for the selected arthrodesis plate. The specially designed Spider (Integra Spider Fusion System, Osteotec, UK) plate or Hubcap (Hubcap 4-corner fusion plate, Acumed, Hampshire, UK) was used. The screw placement was checked on radiographs and the K-wires were removed and bone grafts taken from iliac crest placed between the 4 bones. After surgery, the wrist was immobilized in a plaster cast for 6 to 8 weeks. When fusion was satisfactory, wrist mobilization was allowed under supervision of a therapist.

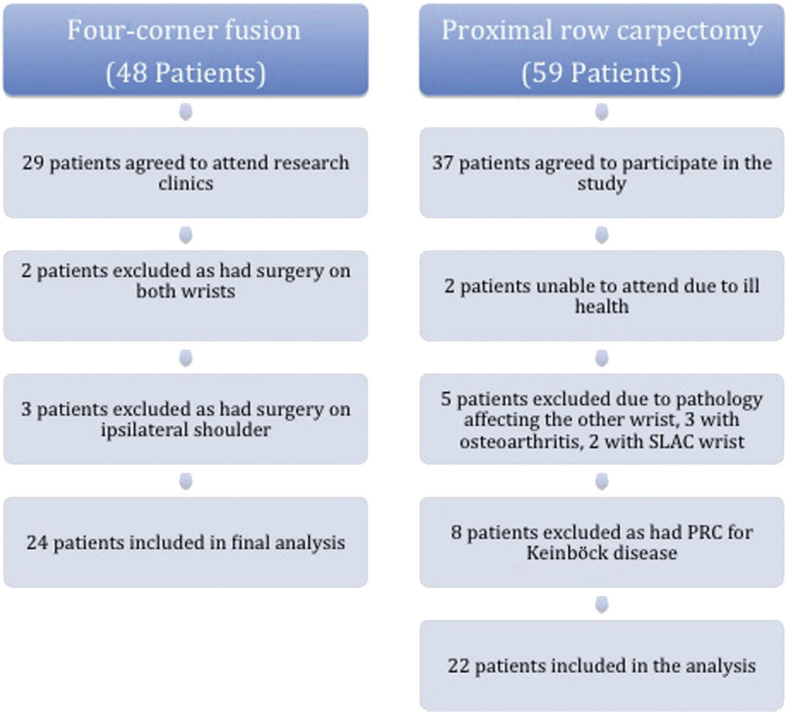

FIGURE 1: Flow diagram showing patients in both study groups included in the study.

The PRC was also done through a dorsal longitudinal incision with an inverted T-shaped capsular approach. The posterior interosseous nerve was divided. While protecting the palmar ligaments and the cartilage on the surface of the capitate and lunate fossa of the radius, we excised the scaphoid, lunate, and triquetrum. The radial styloid was resected to avoid impingement. Postoperatively all patients had the wrist immobilized in a plaster cast for 10 to 14 days, followed by mobilization.

At review, we assessed range of motion, grip strength, and function. We used a flexible electro- goniometer (XM-65, Biometrics Ltd, Gwent, UK) to assess range of wrist movement with twin axis sensors to measure the relative angles between the 2 endblocks. The specifications of this goniometer have been examined and validated [14] and the system was found to be reliable and accurate.[15] The telescopic endblock of the electrogoniometer was attached to the dorsal skin surface over the third metacarpal [16] and the proximal endblock was attached to the dorsum of the forearm in a straight line with the distal block. We performed all assessments in a standard position with the patient seated on a chair with shoulders in a neutral position, the upper arms relaxed, and the el- bows held in 90° flexion with the forearm in full pronation. Patients were asked to perform 5 maximum circumduction movements of the wrist with the hand held in a light fist. Direction of circumduction was clockwise for the right hand and counterclockwise for the left. Patients were asked to move the wrists at a comfortable speed.

We processed the recording with commercial software (MATLAB 7.8, Math Works, Inc, Natick, MA) to derive summary measures. The characteristics of circumduction, such as the shape, size, and orientation, have been previously presented in detail.[17] The MATLAB software allowed extraction of the flexion-extension arc, radioulnar deviation arc, area, circumference, and velocity of circumduction. This software was also used to generate 2-dimensional Lissajous figures (circumduction ellipse) by plotting the output from the electrogoniometer (Figure 2). The circumduction curves were divided into 4 quadrants to study the velocity and smoothness of movement, which was assessed by the number of zero-crossings [17] of the acceleration signal in each quadrant (Figure 3A). The angle of the oblique plane of the maximum distance line was used to measure the orientation of the circumduction curve in relation to the flexion and extension axis (Figure 3B). The mean of the electrogoniometer readings in the x-axis and y-axis during circumduction identified the center of the ellipse.

We assessed grip strength with a pinch/grip analyzer (MIE, Medical Research Ltd, Leeds, UK) that produces reliable and repeatable results.[18] The patient was asked to exert maximum grip and sustain it for 60 seconds. This allowed assessment of peak grip strength and endurance of the affected and unaffected hand. Data collected were also processed with MATLAB software. For both hands, the variables derived from the trace were peak force, slope of the force time curve, area under the curve, and SD of the fitted line (Figure 4).

We used patient-reported outcome measures to study hand function: the Michigan Hand Questionnaire (MHQ) and the Patient Evaluation Measure (PEM). The MHQ evaluates overall hand function, activities of daily living, pain, work performance, aesthetics, and patient satisfaction. The right and left hands were assessed individually. This questionnaire is reliable and valid for wrist and hand outcomes.[19] The PEM evaluates the process of treatment and the current state of the hand but also provides an overall assessment of the hand and wrist and is reliable, valid, and responsive for assessing wrist disorders.[20,21] Higher PEM scores indicate greater disability.

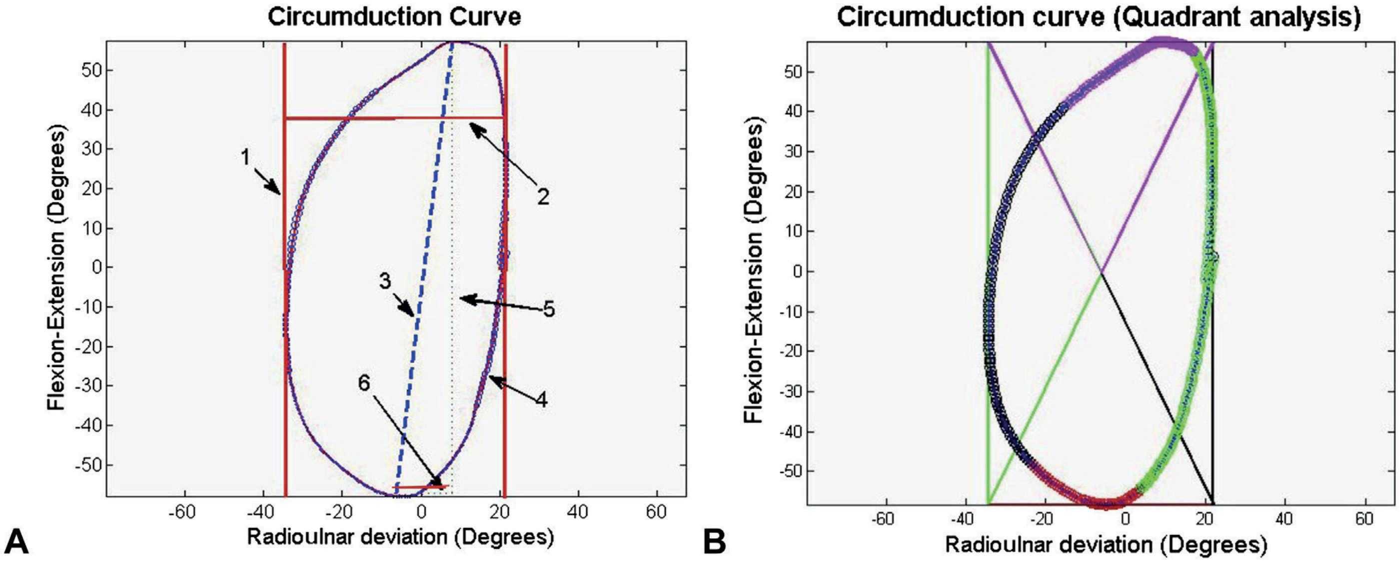

FIGURE 2: A Lissajous figures measure extension flexion arc (*1*), radioulnar deviation arc (*2*), oblique plane of the circumduction curve (*3*), circumference of circumduction (*4*), and maximum vertical distance (*5*) for oblique plane and maximum horizontal distance (*6*) for the oblique plane. The obliquity was clockwise or counterclockwise from the vertical flexion and extension plane depending on whether the right or left hand was assessed. **B** Quadrant analysis allowed the measurement of smoothness and rate in each of the quadrants. (Reprinted with permission from Singh HP, Dias JJ, Slijper H, Hovius S. Assessment of velocity, range, and smoothness of wrist circumduction using flexible electrogoniometry. *J Hand Surg Am*. 2012;37(11):2331e2339. Copyright © Elsevier, Inc. [17])

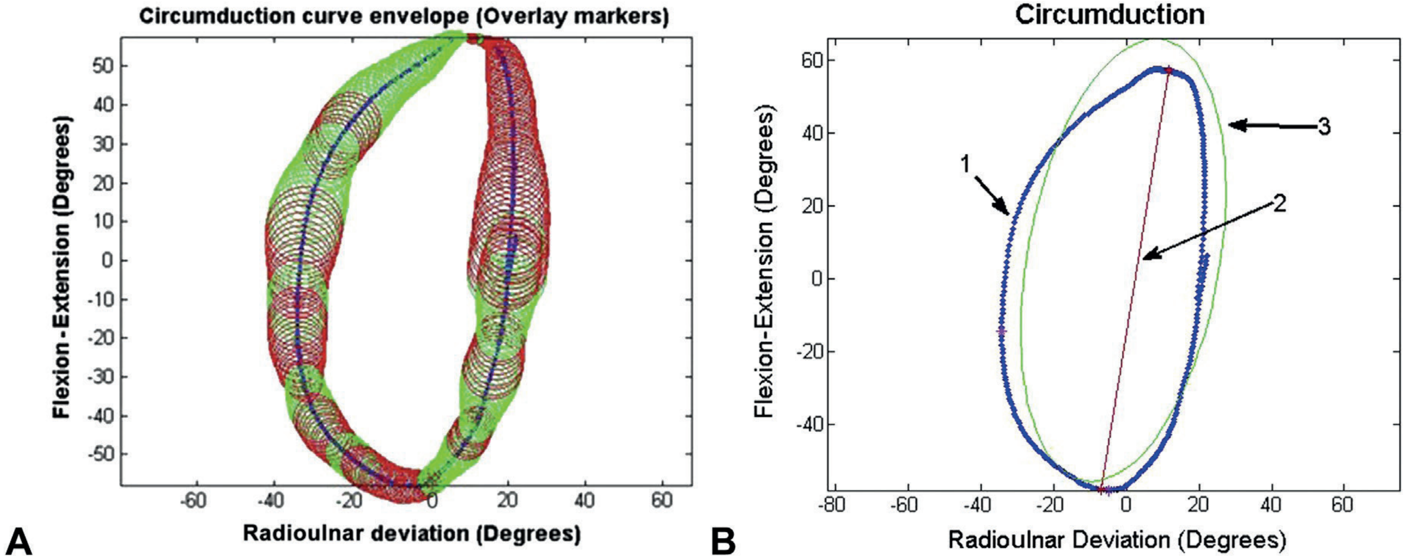

FIGURE 3: A Circumduction curve with overlay of unfilled coloured markers indicating the velocity of movement: green markers indicate acceleration, red markers show deceleration, and transition indicates the 0 point of change in direction of velocity. **B** The ellipse (blue oval) overlay method was used to measure the area of the circumduction curve (*1*). The red line (*2*) correlates with the oblique plane of circumduction curve, and the ellipse (green oval; *3*) overlaid 85% of the data points of the curve.

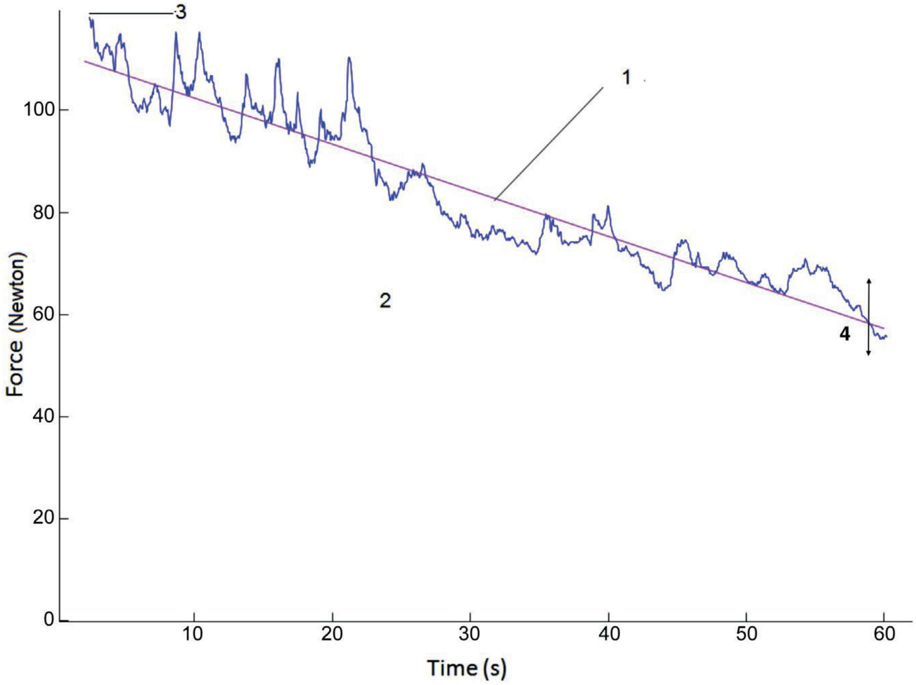

FIGURE 4: Force time curve parameters were selected to quantify the grip strength. *1*, slope of the grip strength calculated from the 60 seconds of force data indicating level of fatigue occurring during the 60 seconds (steeper slope ¼ more fatigue). *2*, area under the force curve (force time integral) is a measure of overall grip force performance. *3*, peak force is a measure of maximum grip strength. *4*, standard deviation of data around the fitted line (SD detrended) based on orthogonal distances from data points to the fitted line (quantifying patients' ability to produce a stable level of force for a period of time).

We calculated mean values and SD of data collected from objective and subjective measures. Because the 2 groups had a dissimilar mean duration since surgery (47 months after a PRC and 72 months after a FCF) (Table 1), data from each group were analyzed independently and presented as a percentage of the nonsurgical hand. We also examined data from the FCF patients with a similar follow-up as the PRC group separately. Direct comparison was not attempted for range of motion, grip strength, or outcome variables.

RESULTS

TABLE 1. Demographic characteristics of patients with PRC at 6 to 47 months, FCF at 10 to 49 months, and FCF at 10 to 148 months.

		PRC (Follow-up 6 - 47 mo)		FCF (Follow-up 10- 49 mo)		FCF (Follow-up 10-148 mo)	
		Mean (SD)	**Count/** *Range*	**Mean (SD)**	**Count/** *Range*	**Mean (SD)**	**Count/** *Range*
Number			**22**		**9**		**24**
Centre		**The Netherlands**		**UK**		**UK**	
Age at surgery, y		51 (11)		50 (14)		49 (10)	
Age at Follow-up, y		53 (11)		53 (14)		55 (10)	
Time since surgery, mo		24	*(6-47)*	29	*(10-49)*	72	*(10-148)*
Immobilization in plaster, wk		2		6		6	
Sex	*Male*		18		8		17
	Female		4		1		7
Hand dominance	*Right*		22		8		22
	Left		0		1		2
Side of surgery	*Right*		15		7		15
	Left		7		2		9
Side of surgery is dominant	*Yes*		15		7		15
	No		7		2		9

We examined 46 patients, mean age 54 years (range, 18e82 y). There were 11 women and 35 men 2 were left-handed. Twenty-four patients had a scaphoid excision and a FCF in the UK and 22 had a PRC in The Netherlands for either an SLAC or SNAC wrist. Patients in the 2 groups were similar regarding age, hand dominance, and sex distribution (Table 1).

The flexion-extension component in circumduction in the surgically treated wrist was 65% of the nonsurgical wrist after a PRC, 41% after FCF with equal follow-up as PRC, and 51% of the nonsurgical side in the total FCF group (Table 2). The radioulnar deviation component in circumduction in the surgical wrist was similar but decreased after either procedure. The mean area of circumduction of the surgical wrist was similar after a PRC and a FCF and was 30% of the nonsurgical wrist. The mean area of circumduction for the nonsurgical wrist was similar in the 2 groups.

The center of the circumduction ellipse after a PRC was in the extension and ulnar deviation quad- rant and was closer to the center of the circumduction ellipse of the opposite wrist; however, the center of circumduction ellipse for a FCF was in the flexion and radial deviation quadrant (Fig. 5).

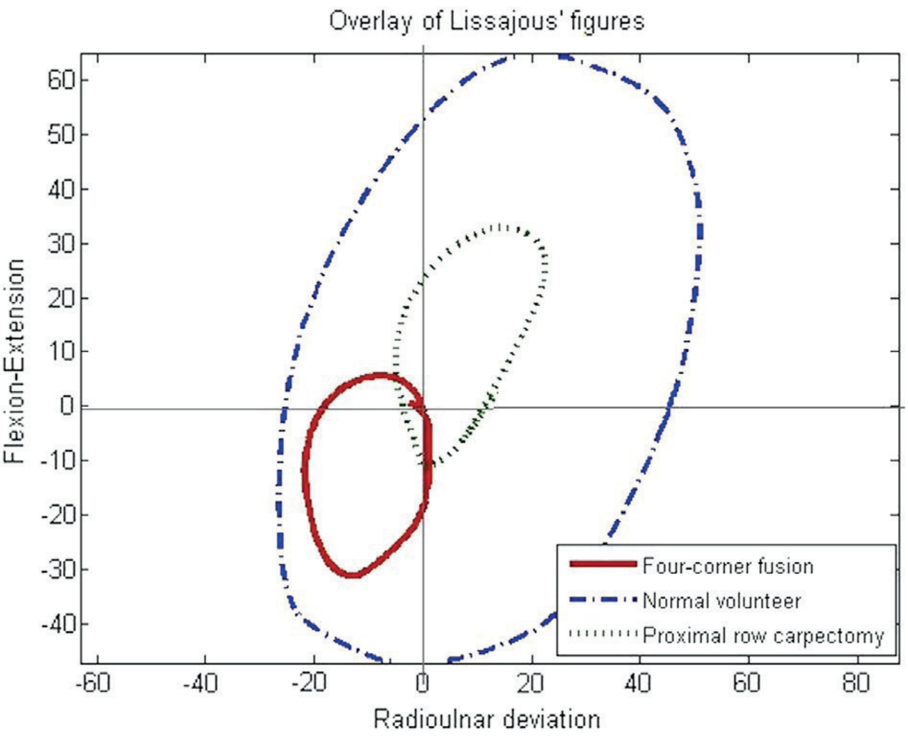

FIGURE 5. Circumduction curves (Lissajous XY figures) of FCF and PRC overlaid on the circumduction curve of a normal volunteer, showing the difference in the area of circumduction.

The orientation of the plane of circumduction was 22° to the vertical flexion-extension plane after a PRC. However, after a FCF the plane was more vertical (90), which was closer to the plane of flexion- extension (Table 2).

The mean velocity of wrist circumduction was 52% of the nonsurgical wrist after PRC, 29% after FCF with equal follow-up as PRC, and 35% in the total FCF group (Table 3). Compared with the nonsurgical wrist, the time taken to complete one circumduction cycle was less after a PRC than after a FCF.

The smoothness of movement of the wrist during circumduction (Fig. 6) after a PRC was similar to the nonsurgical side. However, the smoothness was less after a FCF (Table 4). Compared with the nonsurgical side, peak grip strength and area under the force time curve on the operated side were 81% after a PRC, 51% after FCF with equal follow-up, and 59% in the total FCF group (Table 5). Patients who had a PRC showed a greater drop in strength over 60 seconds because the slope was steeper (Table 5). The MHQ score was 92% of the nonsurgical side after a PRC and 77% in the total FCF group. The PEM score was the lower after a PRC (Table 6).

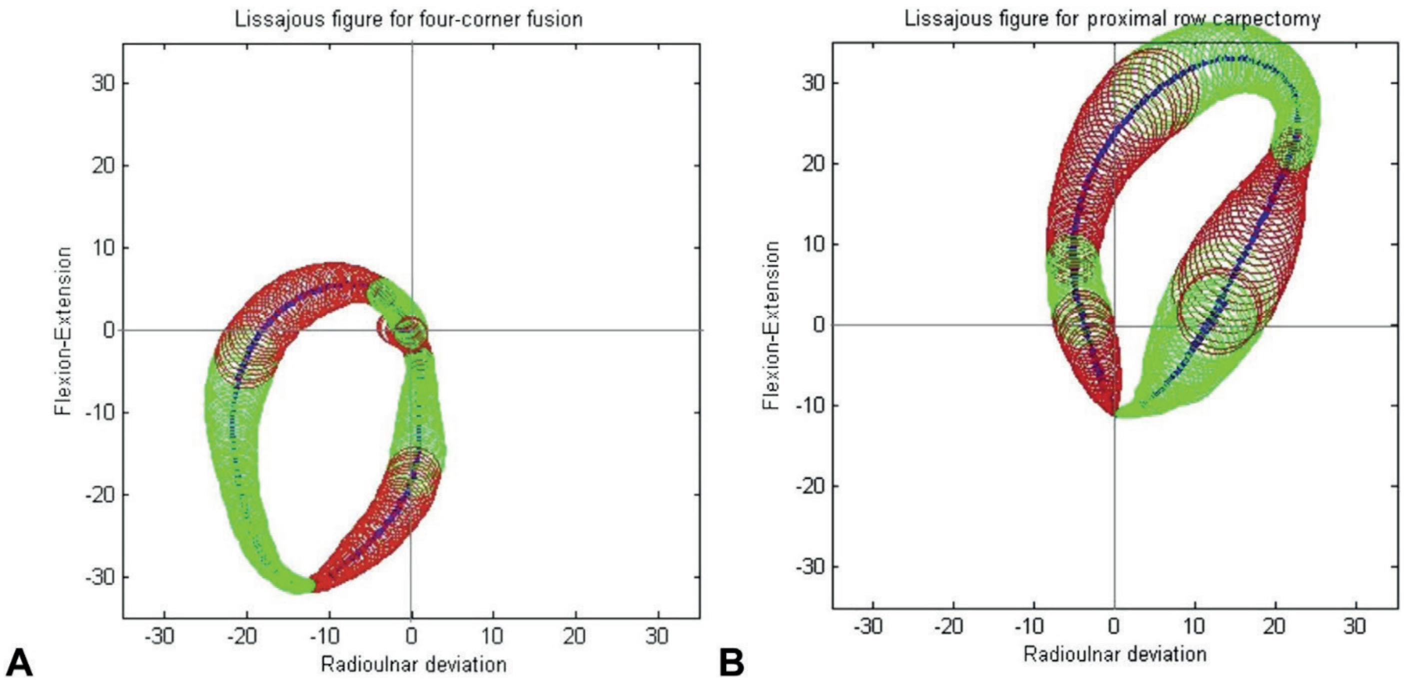

FIGURE 6: A Circumduction curves (Lissajous *XY* figures) for FCF and **B** PRC indicating the obliquity of the plane in PRC. The velocity of movement was faster after PRC, as indicated by the width of the overlay green (acceleration) and red (deceleration) circles. Gray lines indicate the center of the axes.

In the PRC group, 3 patients needed treatment for de Quervain disease after initial surgery. Two patients in FCF group appeared to have delayed or partial union on initial radiographs; however, they remained clinically asymptomatic and subsequently demonstrated fusion on radiographs at 6 months. One patient had removal of prominent screws of the Spider plate after FCF. No other patients required further bony intervention owing to progression of disease or persistence of symptoms.

TABLE 2. Range of circumduction variables in surgically treated hand of patients with PRC at 6 to 47 months, FCF at 10 to 49 months, and FCF at 10 to 148 months: Relationship to nonsurgical hand

Range of Circumduction (degrees)	PRC (Follow-up 6 - 47 mo)		FCF (Follow-up 10 - 49 mo)		FCF (Follow-up 10 -148 mo)	
	Mean	SD	Mean	SD	Mean	SD
Surgical hand						
Flexion- extension in circumduction	60	18	36	14	46	24
Radio ulnar deviation in circumduction	28	11	23	9	29	14
Area of circumduction	1302	878	609	394	1233	1347
Circumference of circumduction	149	44	95	34	125	62
Angle of Oblique circumduction plane	22	13	12	11	9	12
Nonsurgical hand						
Flexion- extension in circumduction	91	18	90	26	92	23
Radio ulnar deviation in circumduction	55	9	42	19	50	16
Area of circumduction	3842	1461	2822	1935	3572	1801
Circumference of circumduction	238	43	220	67	234	60
Angle of Oblique circumduction plane	14	10	13	11	12	8

TABLE 3. Velocity of circumduction in surgically treated hand of patients with PRC at 6 to 47 months, FCF at 10 to 49 months, and FCF at 10 to 148 months: Relationship to nonsurgical hand

Velocity of Circumduction	PRC (Follow-up 6 - 47 mo)		FCF (Follow-up 10 - 49 mo)		FCF (Follow-up 10 - 148 mo)	
	Mean	SD	Mean	SD	Mean	SD
Surgical hand						
Velocity (degrees/s)	90	30	56	34	53	35
Velocity in flexion (degrees/s)	48	53	76	58	50	16
Velocity in radial deviation (degrees/s)	59	59	37	27	23	12
Velocity in extension (degrees/s)	94	70	72	47	69	25
Velocity in ulnar deviation (degrees/s)	58	71	46	46	17	12
Time taken for one cycle, s	1.7	0.6	2	1.6	3	2
Nonsurgical hand						
Velocity (degrees/s)	172	60	192	63	151	63
Time taken for one cycle, s	1.5	0.5	1.2	0.5	1.7	0.8

TABLE 4. Smoothness of circumduction in surgically treated hand of patients with PRC at 6 to 47 months, FCF at 10 to 49 months, and FCF at 10 to 148 months: Relationship to nonsurgical hand

Smoothness of Circumduction, n of zeros/s	PRC (Follow-up 6 - 47 mo)		FCF (Follow-up 10- 49 mo)		FCF (Follow-up 10-148 mo)	
	Mean	SD	Mean	SD	Mean	SD
Surgical hand						
Smoothness	11	2	20	16	28	6
Smoothness Flexion	3	1	6	5	7	7
Smoothness Radial deviation	3	1	3	2	7	7
Smoothness Extension	5	3	5	5	9	8
Smoothness Ulnar deviation	1	1	5	6	6	7
Nonsurgical hand						
Smoothness	11	6	8	3	11	5

TABLE 5. Grip strength (Force time curves) variables in surgically treated hand of patients with PRC at 6 to 47 months, FCF at 10 to 49 months, and FCF at 10 to 148 months: Relationship to nonsurgical hand

Variable	PRC (Follow-up 6 - 47 mo)		FCF (Follow-up 10- 49 mo)		FCF (Follow-up 10-148 mo)	
	Mean	SD	Mean	SD	Mean	SD
Peak strength, *N* *Surgical hand*	229	69	157	79	165	79
Nonsurgical hand	284	97	309	154	281	109
Area under the curve *(N-s)* *Surgical hand*	12835	3929	8640	4446	8777	4562
Nonsurgical hand	15930	5462	16993	6110	15312	5671
Slope of curve (surgical)	-2	1	-1	1	-1	1
Standard deviation of slope (surgical)	8	3	7	3	9	10
Intercept (surgical), N	195	59	124	85	127	74
Time (surgical), s	56	2	55	5	52	7

TABLE 6. Michigan Hand Questionnaire (MHQ) and Patient Evaluation Measure (PEM) in patients with PRC at 6 to 47 months, FCF at 10 to 49 months, and FCF at 10 to 148 months

Variable	PRC (Follow-up 6 - 47 mo)		FCF (Follow-up 10- 49 mo)		FCF (Follow-up 10-148 mo)	
	Median	Range	Median	Range	Median	Range
MHQ						
Surgical hand	87	61-100	62	30-82	70	18-99
Nonsurgical hand	95	78-100	85	55-97	91	55-100
PEM	27	14-40	54	22-62	48	17-82

DISCUSSION

The choice of procedure between FCF and PRC is usually based on the intraoperative findings of stage 2 or stage 3 disease, ie, whether or not cartilage on the head of capitate is preserved. Both preserve some wrist motion and can relieve pain, however, previous studies have not identified clear differences in how the wrist functions after these procedures.[4,5,22]

We used a dynamic assessment of grip strength and range of motion and applied 2 different outcome questionnaires to study these 2 surgical procedures performed for stage 2/3 SLAC and SNAC. Electrogoniometric evaluation of circumduction allowed assessment of the wrist during motion and measurement of range, velocity, smoothness, and oblique functional plane of wrist circumduction.[17]

Patients with a PRC were expected to have a greater range of wrist motion than patients with a FCF. In our study, the flexion-extension component of the circumduction of the surgically treated wrist was larger after a PRC than after a FCF (Table 2). However, the radioulnar deviation arc compared with the nonsurgical wrist was similar in both groups. This conforms to the findings of biomechanical studies [23] in which the difference in the arcs of curvature of the lunate facet and head of capitate limited the radiocapitate motion to mainly the flexion and extension plane.

Representation of wrist motion as circumduction allowed study of the oblique plane of the circum- duction ellipse.[17] This ellipse lies at an angle to the vertical flexion and extension plane and inclines from dorsal and radial to palmar and ulnar, and could represent the physiological axis of wrist motion.[24] This corresponds to the dart thrower's arc of motion that is postulated to represent an important functional plane of motion.[25,26] The orientation of the oblique plane of the circumduction ellipse was 22° for patients with a PRC, which was similar to the plane in normal volunteers.[17] However, the ellipse was closer to the vertical flexion-extension plane after a FCF, which suggests that these patients lack motion in the oblique dart-throwing functional plane [17] (Figure 5). The midcarpal joint allows most of the dart thrower's motion and is fused in a FCF.

We also found that the location of this area was different after the 2 surgical procedures (Figure 4). Previous studies indicated that wrist disease or pain may affect a specific quadrant of wrist circumduction [27] and most activities of daily living are performed in specific arcs of wrist motion.[28] The change in center of the ellipse may limit the ability to perform specific tasks. A recent comparison of wrist motion and tendon forces after FCF and PRC in cadavers also showed a reduction in wrist ulnar deviation, with more radial deviation after FCF.[29]

Velocity of circumduction of the surgically treated wrist was 35% of the nonsurgical side for the total FCF group, which had the longer-term follow-up, but 29% of the nonsurgical side in the FCF patients with equal (shorter-term) follow-up as the PRC. This suggests that FCF patients experience more restriction in the first years after surgery but improve thereafter. However, our numbers were small and because these are different patients, longer-term studies are required to investigate these findings; similar improvement could occur in the PRC group with longer follow-up.

We used the force time curves to study the impact of a FCF and a PRC on grip sustainability. These have been used before to study the impact of deformity in rheumatoid hands.[8] Peak grip strength and area under the force time curve were higher after a PRC than after a FCF (Table 5). Patients with a FCF cannot assume the preferred position to provide maximum efficiency for the muscle tendon units because this procedure restricts ulnar deviation and extension more than after a PRC.

The MHQ has previously been used after FCF surgery.[30] In our groups, the MHQ score for the surgically treated hand was higher after a PRC than after a FCF, with higher scores in activities of daily living and satisfaction and lower pain scores. There was improvement in outcome scores in the FCF group over time (Table 6).

This study had limitations. A total of 39 patients did not respond to our invitation to attend research clinics and were considered to have not consented. We were limited by the conditions of the ethics approval, which prevented us from approaching patients again because they were deemed not to have agreed to participate in the study. The study populations were from different institutions, so the observed differences could result from surgeon factors or different study populations. However, we used the same method and equipment and present outcomes comparing the surgical with the nonsurgical side. The study populations were similar in demographic variables, with no differences in grip strength or range of motion in contralateral nonsurgical wrists. Ideally, a randomized controlled trial would be most suited to compare the 2 procedures. However, based on our data, 41 patients would be required in each group to show a difference of 21 points (SD) in the flexion-extension arc comparing FCF (mean, 47) against PRC (mean, 60) (power, 80%; a < 0.05, 2-sided t test). In addition, it is difficult to recruit sufficient numbers of patients from one center alone, so comparative and multicenter data are required. Mean times since surgery were different in our groups; however, previous studies indicated that the outcomes of FCF [6] and PRC [31] in patients over 35 years of age do not worsen up to 10 years after surgery. We found improvement in the FCF group in motion, velocity, and outcome scores over time, but this observation is based on only 9 patients with a follow-up of 47 months and needs to be repeated in longer-term studies. Volunteers were not asked to move the wrist at maximum velocity, but at a comfortable speed; and standard instructions were given to both groups of patients.

Based on our findings, PRC provides better flexion-extension with a circumduction curve concentric to the nonsurgical wrist. It remains to be seen whether after a PRC patients could complete activities of daily living quicker than patients after a FCF.

REFERENCES

1. Vender MI, Watson HK, Wiener BD, Black DM. Degenerative change in symptomatic scaphoid nonunion. J Hand Surg Am. 1987;12(4):514e519.
2. Watson HK, Ballet FL. The SLAC wrist: scapholunate advanced collapse pattern of degenerative arthritis. J Hand Surg Am. 1984;9(3): 358e365.
3. Cohen MS, Kozin SH. Degenerative arthritis of the wrist: proximal row carpectomy versus scaphoid excision and four-corner arthrodesis. J Hand Surg Am. 2001;26(1):94e104.
4. Mulford JS, Ceulemans LJ, Nam D, Axelrod TS. Proximal row carpectomy vs four corner fusion for scapholunate (Slac) or scaphoid nonunion advanced collapse (Snac) wrists: a systematic review of outcomes. J Hand Surg Eur Vol. 2009;34(6): 256e263.
5. Wyrick JD, Stern PJ, Kiefhaber TR. Motion-preserving procedures in the treatment of scapholunate advanced collapse wrist: proximal row carpectomy versus four-corner arthrodesis. J Hand Surg Am. 1995;20(6):965e970.
6. Bain GI, Watts AC. The outcome of scaphoid excision and four- corner arthrodesis for advanced carpal collapse at a minimum of ten years. J Hand Surg Am. 2010;35(5):719e725.
7. Dacho AK, Baumeister S, Germann G, Sauerbier M. Comparison of proximal row carpectomy and midcarpal arthrodesis for the treatment of scaphoid nonunion advanced collapse (SNAC-wrist) and scapholunate advanced collapse (SLAC-wrist) in stage II. J Plast Reconstr Aesthet Surg. 2008;61(10):1210e1218.
8. Dias JJ, Singh HP, Taub N, Thompson J. Grip strength characteristics using force-time curves in rheumatoid hands. J Hand Surg Eur Vol. 2013;38(2):170e177.
9. Ojima H, Miyake S, Kumashiro M, Togami H, Suzuki K. Ranges of dynamic motion of the wrist in healthy young and middle-aged men. Ergonomics. 1992;35(12):1467e1477.
10. Smith GA, Nelson RC, Sadoff SJ, Sadoff AM. Assessing sincerity of effort in maximal grip strength tests. Am J Phys Med Rehabil. 1989;68(2):73e80.
11. Stern PJ, Agabegi SS, Kiefhaber TR, Didonna ML. Proximal row carpectomy. J Bone Joint Surg Am. 2005;87(suppl 1):166e174.
12. Moriguchi CS, Carnaz L, Silva LC, et al. Reliability of intra- and inter-rater palpation discrepancy and estimation of its effects on joint angle measurements. Man Ther. 2009;14(3):299e305.
13. Szulc P, Lewandowski J, Marecki B. Verification of selected anatomic landmarks used as reference points for universal goniom- eter positioning during knee joint mobility range measurements. Med Sci Monit. 2001;7(2):312e315.
14. Ojima H, Miyake S, Kumashiro M, Togami H, Suzuki K. Dynamic analysis of wrist circumduction: a new application of the biaxial flexible electrogoniometer. Clin Biomech (Bristol, Avon). 1991;6(4): 221e229.
15. Rawes ML, Richardson JB, Dias JJ. A new technique for the assessment of wrist movement using a biaxial flexible electrogoniometer. J Hand Surg Br. 1996;21(5):600e603.
16. Buchholz B, Wellman H. Practical operation of a biaxial goniometer at the wrist joint. Hum Factors. 1997;39(1):119e129.

17. Singh HP, Dias JJ, Slijper H, Hovius S. Assessment of velocity, range, and smoothness of wrist circumduction using flexible electrogoniometry. J Hand Surg Am. 2012;37(11):2331e2339.

18. Helliwell P, Howe A, Wright V. Functional assessment of the hand: reproducibility, acceptability, and utility of a new system for measuring strength. Ann Rheum Dis. 1987;46(3):203e208.

19. Chung KC, Pillsbury MS, Walters MR, Hayward RA. Reliability and validity testing of the Michigan Hand Outcomes Questionnaire. J Hand Surg Am. 1998;23(4):575e587.

20. Macey AC, Burke FD, Abbott K, et al. Outcomes of hand surgery. British Society for Surgery of the Hand. J Hand Surg Br. 1995;20(6): 841e855.

21. Dias JJ, Bhowal B, Wildin CJ, Thompson JR. Assessing the outcome of disorders of the hand: is the patient evaluation measure reliable, valid, responsive and without bias? J Bone Joint Surg Br. 2001;83(2): 235e240.

22. Vanhove W, De Vil J, Van Seymortier P, Boone B, Verdonk R. Proximal row carpectomy versus four-corner arthrodesis as a treatment for SLAC (scapholunate advanced collapse) wrist. J Hand Surg Eur Vol. 2008;33(2):118e125.

23. Sobczak S, Rotsaert P, Vancabeke M, Van Sint Jan S, Salvia P, Feipel V. Effects of proximal row carpectomy on wrist biomechanics: a cadaveric study. Clin Biomech (Bristol, Avon). 2011;26(7):718e724.

24. Taleisnik J. The Wrist. New York: Churchill Livingstone; 1985.

25. Wolfe SW, Crisco JJ, Orr CM, Marzke MW. The dart-throwing motion of the wrist: is it unique to humans? J Hand Surg Am. 2006;31(9):1429e1437.

26. Crisco JJ, Coburn JC, Moore DC, Akelman E, Weiss AP, Wolfe SW. In vivo radiocarpal kinematics and the dart thrower's motion. J Bone Joint Surg Am. 2005;87(12):2729e2740.

27. Nagy L, Buchler U. Long-term results of radioscapholunate fusion following fractures of the distal radius. J Hand Surg Br. 1997;22(6): 705e710.

28. Ryu JY, Cooney WP III, Askew LJ, An KN, Chao EY. Functional ranges of motion of the wrist joint. J Hand Surg Am. 1991;16(3): 409e419.

29. Debottis DP, Werner FW, Sutton LG, Harley BJ. 4-corner arthrodesis and proximal row carpectomy: a biomechanical comparison of wrist motion and tendon forces. J Hand Surg Am. 2013;38(5):893e898.

30. Chung KC, Watt AJ, Kotsis SV. A prospective outcomes study of four-corner wrist arthrodesis using a circular limited wrist fusion plate for stage II scapholunate advanced collapse wrist deformity. Plast Reconstr Surg. 2006;118(2):433e442.

31. DiDonna ML, Kiefhaber TR, Stern PJ. Proximal row carpectomy: study with a minimum of ten years of follow-up. J Bone Joint Surg Am. 2004;86(11):2359e2365.

CHAPTER 3

Comparison of activities of daily living after proximal row carpectomy or wrist four-corner fusion

M.E. Brinkhorst, H.P. Singh, J.J. Dias, R. Feitz, S.E.R. Hovius

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ABSTRACT

Purpose: Proximal row carpectomy (PRC) and four-corner fusion (FCF) are commonly used surgical techniques to manage stage 2 SNAC or SLAC wrists. Controversy still exists as to which treatment has the best results. Both surgeries lead to different postoperative wrist mobility and therefore to a different ability to make commonly-used hand grips. The purpose of this study is to determine which tasks during activities of daily living are more compromised in PRC and FCF patients.

Methods: The hand function of the operated hand was assessed with the modified Sollerman hand function test in 24 PRC patients and 24 FCF patients. Mean follow up was 23months for PRC patients and 73 months for FCF patients. All tasks of the Sollerman hand function test were timed and compared. All patients completed the Michigan Hand Questionnaire (MHQ) and the Patient Evaluation Measure (PEM).

Results: PRC patients completed the timed Sollerman hand function test significantly quicker than the FCF patients (221sec. vs 241sec.). Most tasks (8 of the 16) were performed significantly quicker by the PRC patients. PRC patients reported better function during ADL and the median PEM score was better in PRC patients compared to FCF patients.

Conclusions: Most tasks were performed significantly quicker by the patients after proxial capectomy. The patients after proximal capectomy reported better function during activities of daily living.

INTRODUCTION

Proximal row carpectomy (PRC) and scaphoid excision with four-corner fusion are commonly used motion-preserving surgical techniques to manage stage 2 scaphoid nonunion advanced collapse (SNAC) or scapholunate advanced collapse (SLAC) wrists. In PRC, a new joint is created between the distal carpal row (capitate) and the radius.[1-3] Four-corner fusion is a more demanding operation which restores midcarpal stability and preserves the anatomical joint.[4, 5] Evaluating hand function is important to assess the ability to perform activities of daily living (ADL).[6, 7] Previous studies compared functional outcome of the PRC and four-corner fusion by assessing range of motion of the wrist and by using questionnaires.[8-13] To our knowledge, the ability to perform tasks of daily living in patients after two surgeries has not been assessed with an objective ADL test.

The Sollerman hand function test examines the ability to perform activities of daily living using different handgrips.[6, 14-17] Recently, the test was modified by timing all the subtasks separately, which gives a more precise overview of the hand function.[18] The timed Sollerman hand function test could give more information about which tasks and grips are more difficult for patients in each study group.[18] This knowledge could assist surgeons in making a more informed choice between these salvage procedures and help counsel patients about the effects of the two procedures on ADL. The aim of this study was to compare the effect of PRC and four-corner fusion on patients' ability to perform ADL by comparing the time taken to perform the tasks in the timed Sollerman test and its related handgrips.

MATERIALS AND METHODS

Study design

Data for this cross-sectional study was collected from patients who had undergone either a PRC or a four-corner fusion for SNAC or SLAC wrist stage 2 or 3 from two separate institutions in the Netherlands and the United Kingdom. The inclusion criteria were that the patients should be older than 20 years; they were treated for post traumatic wrist osteoarthritis, they have never had any other surgical procedures on the wrist; and they had follow-up of more than 6 months. Exclusion criteria were medical history of rheumatoid arthritis, osteoarthritis of digits of the hands, major surgical procedures or neuromuscular pathology affecting the ipsilateral upper extremity, or if the patient had learning disabilities.

Data was collected by two researchers, who were not involved in direct patient care. A standard protocol was agreed for consistency and the second researcher (MB) was trained by the first researcher (HS) who had previous experience using the timed Sollerman test. Demographic data on operative procedures was collected by retrospective chart analysis.

Patients

Information on patients (n=48) who had undergone a four-corner fusion with a spider plate or Hubcap in the period from 2005 to 2011, was retrieved from the database of the Orthopaedic department of the Glenfield Hospital, Leicester (UK). All patients were treated with a technique described below. Twenty-nine patients agreed to attend the research clinic. Two patients were excluded due to surgery on both wrists, 3 patients were excluded due to surgery on their ipsilateral shoulder. Twenty-four patients with a four-corner fusion were included in the analysis.

Data on all patients (n=59) who had a PRC in the from 2006 to 2010, was retrieved from the database of the Plastic Surgery department of the Diakonessenhuis, Utrecht/Zeist, the Netherlands. These patients were treated by one of the two senior hand surgeons. The levels of expertise of both surgeons for these procedures were Level IV (Specialist – highly experienced).[19] Thirty-seven patients agreed to attend the clinic, 2 patients were unable to attend due to illness, 2 patients were excluded as they had surgeries on both wrists, 7 patients were excluded as they had PRC for Kienböck's disease, and other 2 patients were excluded due to osteoarthritis at the base of the thumb on the affected hand. Therefore, twenty-four patients with a PRC were finally included in the analysis.

Verbal and written information was given to all patients before assessment. All patients gave signed consent. Approval by the medical ethical committees from both institutions was obtained (NL: MEC-2010-295 and UK: 08/H0406/221).

Surgical techniques

Four corner fusion

A longitudinal dorsal incision was made followed by a ligament sparing approach to the wrist joint. The posterior interosseous nerve was dissected and divided proximal to the joint. It was confirmed that the cartilage over the lunate and the fossa lunate was intact. The Spider plate (Integra® Spider™ Fusion System, Osteotec, UK) plate or Hubcap (Hubcap four corner fusion plate, Acumed, UK) was placed so that each carpal bone was fixated with screws (2,4mm, self-tapping). Patients stayed in a protective splint or cast for 6-8 weeks. Further mobilization was allowed under guidance of the hand therapy department after confirmation of fusion by radiological assessment.

Proximal Row Carpectomy

A dorsal longitudinal incision was made followed by raising of the third and fourth extensor compartment. Neurectomy of the posterior interosseous nerve was performed in a standard fashion. The scaphoid, lunate, and triquetrum were removed while protecting the palmar ligaments, cartilage on the surface of the capitate and lunate fossa of the radius. The radial styloid was resected to avoid radial impingement if deemed necessary. Postoperatively, all patients stayed in a splint or cast for 7 – 10 days, followed by protective splinting and mobilization under guidance of a hand therapist.

The timed Sollerman hand function test

The Sollerman hand function test is a standardised hand function test consisting of 20 activities of daily living based on seven of the eight handgrips (Supplementary Table 4).[6] We have combined subtasks 13-15 (writing, fold paper and put in envelope, and put paperclip on envelope) and subtasks 18-20 (pack to jug, jug to cup, and cup to jug), because they consisted of similar wrist movements, resulting in a total of 16 subtasks (Supplementary Table 5). In the original Sollerman test, all subtasks were timed and after completion of the test every subtask was scored on a 5 point scale from 0 (task cannot be performed) to 4 (task was easily completed within 20 seconds with the prescribed handgrip).[6] This may lead to the loss of useful information as the original Sollerman test was designed for patients with tetraplegia.

In the present study, we used the modified timed Sollerman hand function test described by Singh et al.[18] All patients were given verbal instructions before each task to explain the appropriate position, prescribed handgrip and method of doing each task as described by Sollerman.[6] Both hands were assessed individually and all subjects performed the test once.

Patient reported outcome

The Michigan Hand Questionnaire (MHQ) and the Patient Evaluation Measure (PEM) were used to evaluate patient-reported outcome and hand function for the two patient groups. The MHQ evaluates overall hand function, ADL, pain, work performance, aesthetics, and patient satisfaction with hand function. It consists of 63 questions with five possible answers, divided into 6 scales (overall function, activities of daily living, work, pain, appearance and satisfaction). Both hands are assessed individually. A higher score indicates a better hand performance except for the pain score where a higher score indicates more pain.[20]

The PEM evaluates the process of treatment, the current state of the hand, and it provides an overall assessment of the wrist and hand. It consists of three parts with a total of 19 questions. The questions focus on symptoms, the impact of the disorder on the patient, the satisfaction and general disability/handicap. A higher score indicates greater disability.[21]

Data Analysis

For the timed Sollerman test, we calculated the median and range of the time taken to complete each individual task with the affected and unaffected hand, and the total time. In addition, we normalized the time of the separate items and the total time by calculating a ratio of the affected hand divided by the unaffected hand and the total to omplete the test was further adjusted for age based on our previous data obtained from 100 healthy volunteers (Singh et al., 2015). The Mann-Whitney U test was used to compare the data of the patients after two surgeries. Statistical significance was set at 0.05.

To control for the multiple testing of all timed Sollerman items, we used the Holm-Bonferroni correction to adjust P levels for multiple tests .

RESULTS

The two groups were similar for hand dominance, sex distribution, side of surgery, age at time of surgery and age at follow-up (online Table 3). The average followup was 23 months for the patient with PCR and 75 months for the patients with four-corner fusion, In the followup course, one patient in the four-corner fusion group reported prominence of the screws of the plate. This plate was removed after radiologically confirmed fusion. Two patients experienced a superficial infection, and one patient developed early signs of complex regional pain syndrome which settled with exercise. No nonunion was reported. In the PRC group, one patient was treated for De Quervain's tenosynovitis. In the four-corner fusion group, 2 patients (a truck driver and a computer assistant) stopped working after surgery. In comparison with the PRC group, all patients continued working after surgery.

The median time to complete the timed Sollerman hand function test with the affected hand was 241 seconds for patients with a four-corner fusion, which was significantly slower than the 221 seconds in patients with a PRC (P = 0.007). Patients with a PRC were significantly quicker in tasks 1, 2, 6, 9, 10, 12, 15 and 16 than the patients with a four-corner fusion (Table 1), which corresponds to better function of the pulp pinch, transverse volar grip, a combination of pulp- and lateral pinch, combination of tripod- and five-finger pinch, and a combination of tripod pinch and diagonal volar grip (online Table 1). The same result was found when the ratio compared to the unaffected wrist was calculated (Table 2). The patients with a four-corner fusion could unscrew the lids with their affected hand significantly quicker than patients with a PRC (Table 1 and 2), which corresponds to a better spherical volar grip. No significant difference was found when comparing the unaffected hand in PRC patients with those of four-corner fusion patients. When adjusting for age and handedness, we found that the median time to complete the test was significantly lower (119%) in patients with a PRC than in patients with a four-corner fusion (135%, P = 0.005). The total time to complete the test with the unaffected hand was not significantly different (116% vs 112%, P = 0.90).

The median total MHQ score for the affected hand (Table 3) in the PRC group was significantly higher than in the four-corner fusion group (P < 0.001), indicating a better hand function in the PRC group. The ADL, Pain, and satisfaction subscores of the PRC patient group showed better results (P < 0.001, < 0.001, and 0.02, respectively). The median PEM score (Table 3) was lower in the PRC group compared to the four-corner fusion group (P < 0.001).

TABLE 1. Results, in seconds, to complete the subtasks of the modified timed Sollerman hand function test for the affected hand

	Subtask	*FCF (n=24)*		*PRC (n=24)*		*P value*	*Holm-Bonferroni P value*
		Median	**Range**	**Median**	**Range**		
1	**Put key into Yale lock, turn 90°**	8	3-12	5	3-20	0.001	0.01*
2	**Pick coins from flat surface, put into purses mounted on wall**	6	4-10	4	3-6	<0.001	< 0.001*
3	**Open/close zip**	11	6-16	12	8-33	0.56	0.56
4	**Coins out of purse**	9	4-17	8	5-16	0.24	1
5	**Wooden blocks**	6	3-10	4	2-8	0.03	0.17
6	**Lift iron**	5	3-7	3	2-6	0.003	< 0.001 *
7	**Turn screwdriver**	9	6-10	10	6-25	0.10	0.57
8	**Nuts on bolts**	29	16-40	24	17-85	0.42	0.84
9	**Unscrew lids**	14	9-17	19	11-51	<0.001	0.003 *
10	**Do up buttons**	36	29-62	24	19-83	<0.001	< 0.001 *
11	**Cut play-doh**	20	10-30	16	10-29	0.02	0.17
12	**Put on tubigrip on other hand**	7	3-10	5	2-10	0.002	0.02 *
13	**Writing + Fold paper put in envelope + paperclip**	38	32-62	39	27-61	0.38	1
14	**Pick up Telephone**	4	2-5	3	2-5	0.34	1
15	**Turn door-handle**	3	2-4	2	1-3	<0.001	0.001 *
16	**1Lpack to jug + jug to cup + cup to jug**	34	24-49	29	20-41	0.001	0.006 *
Total time to complete test		241	204-270	221	204-270	0.007	

FCF: Four-corner fusion; PRC: Proximal row carpectomy.*Null hypothesis that the differences are only by chance rejected by Holm-Bonferroni test.

TABLE 2. Ratio to complete the subtasks of the modified timed Sollerman hand fuction test.

	Subtask	*FCF (n=24)*		*PRC (n=24)*		*P value*	*Holm-Bonferroni P value*
		Median	**Range**	**Median**	**Range**		
1	**Put key into Yale lock, turn 90°**	1.5	0.5-3.5	1	0.5-4	0.035	0.35
2	**Pick coins from flat surface, put into purses mounted on wall**	1.6	0.9-3.2	1	0.7-1.5	<0.001	< 0.001*
3	**Open/close zip**	1.1	0.6-1.9	1	0.6-2.7	0.31	1
4	**Coins out of purse**	1.3	0.4-2.7	1.1	0.5-2.8	0.09	0.70
5	**Wooden blocks**	1.2	0.6-3.0	1.2	0.8-1.7	0.09	0.55
6	**Lift iron**	1.6	0.9-3.4	1.2	6.6-1.6	<0.001	<0.001*
7	**Turn screwdriver**	0.9	0.5-1.2	1	0.5-2.1	0.14	0.72
8	**Nuts on bolts**	1	0.7-2.2	1	0.4-4.4	0.97	0.97
9	**Unscrew lids**	0.8	0.5-1.7	1.1	0.7-2.4	<0.001	<0.001*
10	**Do up buttons**	1.6	1-4.8	1.1	0.6-3.8	0.004	0.048 *
11	**Cut play-doh**	1	0.5-2.5	0.8	0.3-2.2	0.09	0.61
12	**Put on tubigrip on other hand**	1.3	0.6-3	1.1	0.5-2.2	0.31	0.94
13	**Writing + Fold paper put in envelope + paperclip**	1	0.7-1.7	0.7	0.5-1.6	0.022	0.24
14	**Pick up Telephone**	1.2	0.4-3	1.2	5.8-1.9	0.34	1
15	**Turn door-handle**	1.3	0.8-2.9	1.1	0.6-2	0.06	0.55
16	**1Lpack to jug + jug to cup + cup to jug**	1.2	0.8-1.7	1	20-41	0.003	0.039*

Ratio = time affected hand/time unaffected hand. FCF: Four-corner fusion; PRC: Proximal row carpectomy.

*Null hypothesis that the differences are only by chance rejected by Holm-Bonferroni test.

TABLE 3. Results of the patient reported outcomes

	FCF		*PRC*	
	Median	**Range**	**Median**	**Range**
Michigan Hand Questionnaire				
Overall function	63	10-100	68	50-100
ADL	62	4-98	88	61-100
Pain	48	0- 85	10	0-40
Aesthetics	100	13-100	100	75-100
Satisfaction	67	0-100	85	46-100
Total score	69	18-99	87	61-100
Patient Evaluation Measure				
Total score	48	17-82	27	14-40

ADL: activities of daily living; FCF: Four-corner fusion; PRC: proximal row carpectomy

DISCUSSION

Previous studies compared hand function of the patients with PRC and scaphoid excision with four-corner fusion by assessing grip strength and range of motion of the wrist.[8-11] Here we compared activities of daily living and its related hand grip after a four-corner fusion or a PRC.

The Sollerman test was originally developed for tetraplegic patients. Using the original test in our patient group would have given a limited view on the ability to complete activities in daily living, because the patients in these groups are much quicker than tetraplegic patients. As a result, the Sollerman scores in both patient groups would have been the same. Recently, Singh et al. [18] proposed a modification of the Sollerman hand function test. The modified test provided more detailed information about the ability to perform tasks in ADL swiftly, as well as to compare the scores of individual items and their related hand grips by looking at the time to complete a task compared to the original summarised score. As the patients could perform the tasks more quickly after a PRC compared to a four-corner fusion, the clinical impact could be reflected in greater satisfaction for patients as indicated by the questionnaires.

Different studies showed that the ability to perform ADL is related to specific arcs of wrist motion [22-24]. Four-corner fusion provides a larger radioulnar deviation arc compared to the PRC.[25] Patients with a PRC have a better flexion-extension arc and the position of the ellipse of circumduction is more similar to an unaffected hand. Nichols et al. [26] examined the torque needed to maintain functional postures by comparing kinematic computer models of the wrists with PRC or four-corner fusion. They found that a PRC wrist required less torque than a four-corner fusion wrist even compared to normal wrists. Patients with a PRC are therefore expected to be less limited in performing most activities of daily living than patients with a four-corner fusion. Wolff et al [27] compared kinematic coupling and performance during two functional tasks (dart throwing motion and hammering) in patients following four-corner fusion and PRC. They concluded that PRC subjects performed better on kinematic and performance variables. The above mechanical data suggest that PCR may favour wrist function than four-corner fusion.

Debottis et al. [28] found that larger peak tendon forces were required in the wrists after four-corner fusion compared to those after PRC t to achieve identical wrist motions. In our study, we found that most activities of daily living were indeed performed more quickly by the patients with a PRC compared to patients after four-corner fusion. An exception was the “opening jars” task, which was performed more quickly by the patients after four-corner fusion. For this task, a large wrist torque is required. The tests using MHQ and PEM show that patients experienced fewer disabilities in ADL and greater satisfaction after PRC compared to four-corner fusion. The pain reported in the two groups was also less after a PRC.

This study has its limitations. The number of patients in both groups is small as around 50% of each intervention group were reviewed. This was because of restrictions imposed by our Ethics Committee. However, patients not reviewed were demographically similar to the patients reviewed. A second limitation is that the modified Sollerman test is relatively new, which has not been tested for its reliability and reproducibility. The third limitation is that the PRC group was retrieved from different institutions, but the patients with the four-corner fusion was from a single institute. A greater number of surgeons have involved in the care of patients with PRC. Furthermore, difference in ADL might have resulted from a longer immobilisation period after four-corner fusion (6 weeks versus 1 week in the PRC group) and the average length of followup was longer in the patients with four-corner fusion. However, the results of all patients were determined with minimal followup of 6 months.

Overall, results of this study show that patients with PRC had better functional outcome compared to patients with four-corner fusion using the modified Sollerman test. ADL were performed more quickly by patients with PRC than patients with four-corner fusion, except for activities requiring wrist torque strength, such as opening a jar.

REFERENCES

1. Blankenhorn, B.D., et al., Carpal kinematics after proximal row carpectomy. J Hand Surg Am, 2007. 32(1): p. 37-46.
2. Imbriglia, J.E., et al., Proximal row carpectomy: clinical evaluation. J Hand Surg Am, 1990. 15(3): p. 426-30.
3. Inglis, A.E. and E.C. Jones, Proximal-row carpectomy for diseases of the proximal row. J Bone Joint Surg Am, 1977. 59(4): p. 460-3.
4. Merrell, G.A., E.M. McDermott, and A.P. Weiss, Four-corner arthrodesis using a circular plate and distal radius bone grafting: a consecutive case series. J Hand Surg Am, 2008. 33(5): p. 635-42.
5. Baratz, M.E. and A. Towsen, Midcarpal arthrodesis: four-bone technique. Tech Hand Up Extrem Surg, 1997. 1(4): p. 237-44.
6. Sollerman, C. and A. Ejeskar, Sollerman hand function test. A standardised method and its use in tetraplegic patients. Scand J Plast Reconstr Surg Hand Surg, 1995. 29(2): p. 167-76.
7. Jonsson, B. and S.E. Larsson, Hand function and total locomotion status in rheumatoid arthritis. An epidemiologic study. Acta Orthop Scand, 1990. 61(4): p. 339-43.
8. Mulford, J.S., et al., Proximal row carpectomy vs four corner fusion for scapholunate (Slac) or scaphoid nonunion advanced collapse (Snac) wrists: a systematic review of outcomes. J Hand Surg Eur Vol, 2009. 34(2): p. 256-63.
9. Bisneto, E.N., et al., Comparison between proximal row carpectomy and four-corner fusion for treating osteoarthrosis following carpal trauma: a prospective randomized study. Clinics (Sao Paulo), 2011. 66(1): p. 51-5.
10. Dacho, A.K., et al., Comparison of proximal row carpectomy and midcarpal arthrodesis for the treatment of scaphoid nonunion advanced collapse (SNAC-wrist) and scapholunate advanced collapse (SLAC-wrist) in stage II. J Plast Reconstr Aesthet Surg, 2008. 61(10): p. 1210-8.
11. Baumeister, S., et al., [Functional results after proximal row carpectomy (PRC) in patients with SNAC-/SLAC-wrist stage II] Funktionelle Ergebnisse nach Entfernung der proximalen Handwurzelreihe bei SNAC- und SLAC-Wrist Stadium II. Handchir Mikrochir Plast Chir, 2005. 37(2): p. 106-12.
12. Richou, J., et al., Proximal row carpectomy: long-term results. Chir Main, 2010. 29(1): p. 10-5.
13. Bain, G.I. and A.C. Watts, The outcome of scaphoid excision and four-corner arthrodesis for advanced carpal collapse at a minimum of ten years. J Hand Surg Am, 2010. 35(5): p. 719-25.
14. Blomgren, I., et al., Hand function after replantation or revascularization of upper extremity injuries. A follow-up study of 21 cases operated on 1979-1985 in Goteborg. Scand J Plast Reconstr Surg Hand Surg, 1988. 22(1): p. 93-101.
15. Draviaraj, K.P. and I. Chakrabarti, Functional outcome after surgery for Dupuytren's contracture: a prospective study. J Hand Surg Am, 2004. 29(5): p. 804-8.
16. Brogardh, C., A.L. Persson, and B.H. Sjolund, Intra- and inter-rater reliability of the Sollerman hand function test in patients with chronic stroke. Disabil Rehabil, 2007. 29(2): p. 145-54.

17. Lindqvist, A., M. Hjalmarsson, and O. Nilsson, DASH and sollerman test scores after hand injury from powered wood splitters. J Hand Surg Eur Vol, 2011. 36(1): p. 57-61.

18. Singh, H.P., J.J. Dias, and J.R. Thompson, Timed Sollerman hand function test for analysis of hand function in normal volunteers. J Hand Surg Eur Vol, 2015. 40(3): p. 298-309.

19. Tang, J.B., Re: Levels of experience of surgeons in clinical studies. J Hand Surg Eur Vol, 2009. 34(1): p. 137-8.

20. Chung, K.C., et al., Reliability and validity testing of the Michigan Hand Outcomes Questionnaire. J Hand Surg Am, 1998. 23(4): p. 575-87.

21. Dias, J.J., et al., Assessing the outcome of disorders of the hand. Is the patient evaluation measure reliable, valid, responsive and without bias? J Bone Joint Surg Br, 2001. 83(2): p. 235-40.

22. Ryu, J.Y., et al., Functional ranges of motion of the wrist joint. J Hand Surg Am, 1991. 16(3): p. 409-19.

23. Brumfield, R.H. and J.A. Champoux, A biomechanical study of normal functional wrist motion. Clin Orthop Relat Res, 1984(187): p. 23-5.

24. Murgia, A., et al., Marker placement to describe the wrist movements during activities of daily living in cyclical tasks. Clin Biomech (Bristol, Avon), 2004. 19(3): p. 248-54.

25. Singh, H.P., et al., Dynamic assessment of wrist after proximal row carpectomy and 4-corner fusion. J Hand Surg Am, 2014. 39(12): p. 2424-33.

26. Nichols, J.A., M.S. Bednar, and W.M. Murray, Orientations of wrist axes of rotation influence torque required to hold the hand against gravity: a simulation study of the nonimpaired and surgically salvaged wrist. J Biomech, 2013. 46(1): p. 192-6.

27. Wolff, A.L., et al., Surgical Treatments for Scapholunate Advanced Collapse Wrist: Kinematics and Functional Performance. J Hand Surg Am, 2015. 40(8): p. 1547-53.

28. Debottis, D.P., et al., 4-corner arthrodesis and proximal row carpectomy: a biomechanical comparison of wrist motion and tendon forces. J Hand Surg Am, 2013. 38(5): p. 893-8.

APPENDICES

Supplementary TABLE 4
Supplementary TABLE 5

Supplementary TABLE 4. 20 tasks of the Sollerman hand function test and their corresponding handgrip as described by Sollerman. [1]

		Pulp Pinch	Lateral Pinch	Tripod Pinch	Five-Finger Pinch	Diagonal Volar Pinch	Transverse Volar Pinch	Spherical Volar Grip
1	Put key into Yale lock and turn 90°	X	X					
2	Pick op coins from flat surface and put into purse	X						
3	Open/close purses	X	X					
4	Take coins out of purse	X						
5	Lift wooden blocks over 5cm high edge				X			
6	Lift iron over 5cm high edge						X(pronated)	
7	Turn screw with screwdriver					X		
8	Pickup nuts and put on bolts	X	X	X				
9	Unscrew lids of jars							X
10	Do up buttons	X	X					
11	Cut play-doh with knife and fork			X		X		
12	Put on tubigrip on other hand		X		X			
13	Write with a pen			X				
14	Fold paper and put it into an envelope		X		X			
15	Put paperclip on envelope	X	X					
16	Pick up relephone and put it to the ear					X		
17	Turn door handle 30°						X	
18	Pour water from 1L pack to jug				X			
19	Pour water from jug to cup						X	
20	Pour water from cup to jug	X	X					

Supplementary TABLE 5. Subtasks of timed Sollerman hand function test.

no.	Subtask
1	Put key into Yale lock, turn 90°
2	Pick coins up from flat surface, put into purses mounted on wall
3	Open/close zip
4	Pick up coins from purse
5	Lift wooden cubes over edge of 5 cm in height
6	Lift iron over edge 5cm in height
7	Turn screw with screwdriver
8	Pick up nuts and put on bolds
9	Unscrew lid of jars
10	Do up buttons
11	Cut play-doh with knife and fork
12	Put on Tubigrip stocking on the other hand
13	Write with pen + Fold paper and put in envelope + put paperclips on envelope
14	Lift telephone receiver, put to ear
15	Turn door-handle 30°
16	Pour water from 1Lpack to jug + pour from jug to cup + pour from cup to jug

CHAPTER 4

Results of the Universal 2 prosthesis in noninflammatory osteoarthritic wrist

M.E. Brinkhorst, R.W. Selles, J.J. Dias, H.P. Singh, R. Feitz, T.M. Moojen, S.E.R. Hovius

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ABSTRACT

Purpose: Many treatment options are available for wrist osteoarthritis, with the objective of decreasing pain and preserving function. In later stages when midcarpal and radiocarpal osteoarthritis occur, two choices remain: total wrist arthrodesis or total wrist arthroplasty. The purpose of this study is to present the short-term functional changes following total wrist arthroplasty with the Universal 2 Total Wrist System in patients with noninflammatory wrist osteoarthritis.

Methods: Patients with severe noninflammatory wrist osteoarthritis were assessed pre-operatively, 6 and 12 months after surgery using range of motion, grip strength, pain and DASH score. Additional assessment was performed after one year for range of motion using a biaxial electrogoniometer, grip strength, DASH, and the Michigan Hand Questionnaire.

Results: All range of motion directions and grip strength did not change from preoperatively. DASH score improved from 53 preoperatively to 14 during latest follow-up. Median patients satisfaction score, decreased with approximately 20 points during last follow-up.

Conclusions: The relatively good DASH score combined with the partly maintained wrist range of motion indicates that reconstruction with the Universal 2 Total wrist prosthesis should be considered in patients with end-stage noninflammatory wrist osteoarthritis.

INTRODUCTION

Posttraumatic (noninflammatory) osteoarthritis of the wrist and rheumatoid arthritis (RA) are the two common causes of wrist diseases associated with end stage wrist arthropathy. The commonest forms of posttraumatic wrist osteoarthritis (PTOA) is scapholunate advanced collapse (SLAC), followed by the scaphoid nonunion advanced collapse (SNAC) wrist.[1] Many surgical options are available for wrist osteoarthritis, with the objective of decreasing pain and preserving function. The choice depends on the stage and aetiology of the osteoarthritis, age and lifestyle of the patient. In end stages when midcarpal and radiocarpal joints are affected, two choices remain: total wrist arthrodesis or total wrist arthroplasty.

Although all wrist range of motion is lost, some surgeons prefer total wrist arthrodesis due to its predictable outcomes such as good pain relief and a low failure rate.[2, 3] Preference for arthrodesis is based on studies predominantly on RA patients. Residual pain and substantial dysfunction have been reported after arthrodesis in noninflammatory patients.[4, 5] Furthermore, RA patients are prone to joint subluxation, a higher infection risk, and have worse bone stock [2, 6] making translation of results from RA to osteoarthritis less representative. In contrast, PTOA patients are usually younger, their problem is isolated, and they have higher functional demands resulting in a higher risk for early arthroplasty failure. A systematic review concluded that total wrist arthroplasty has similar functional outcome and patient reported outcome as total wrist arthrodesis in RA patients.[7]

The first total wrist arthroplasty was performed by Gluck in 1890.[8] The surgical technique, design, and mechanism of the total wrist prosthesis have evolved over time with improve stability and outcome.[9] The Universal 2 Total Wrist System (Integra Life Sciences) is a fourth-generation prosthesis and several studies have already reported good results with this implant for RA patients, but they have not been reported for noninflammatory patients.[10-13] In this study, we present the early functional results following total wrist arthroplasty with the Universal 2 Total Wrist System in patients with severe noninflammatory wrist osteoarthritis.

MATERIALS AND METHODS

Population

Between January 2006 and January 2011, 21 PTOA patients (two distal radius fractures, four SNAC wrists and 15 SLAC wrists grade 3/4) and two Kienböck's patients were treated with a Universal 2 Total Wrist System at the Plastic Surgery department of the Diakonessenhuis, Utrecht/Zeist, the Netherlands. Of these 23 noninflammatory patients, 14 (61%) were female, 13 right wrists and 14 dominant wrists were affected. Mean age of the patients at time of surgery was 60 years (31-80 years). Pre-operative data was available from 18 patients. One patient was treated with Universal 2 prosthesis for both wrists. Seven patients had previous surgery, such as: scapholunate ligament reconstruction, four-corner fusion, wrist arthrodesis, and shortening of the radius or ulna. The medical ethics committee approved this study (MEC-2010-295) and included patients gave consent.

Surgical technique and postoperative protocol

Two hand surgeons (RF and TM) performed all surgeries. Each patient had a standard surgical approach and postoperative management, based on the technique described by Menon [14] and Adams.[15] All patients received a single-dose of prophylactic antibiotics. Through a dorsal longitudinal incision the wrist joint was exposed and the joint entered through the third extensor compartment by an inverted T-shaped incision of the dorsal wrist capsule. In 11 patients the distal ulna was resected through its neck, because the distal radio-ulnar joint was arthritic or interfered with the radial component. The proximal and distal surfaces were prepared using cutting blocks, and trial components were placed. After testing wrist motion and stability, the final prosthesis was inserted (without cement and with two screws for the distal component), and the alignment was radiographically checked. The dorsal capsule was closed. After surgery, the wrist was immobilized in a plaster of Paris cast for one week, followed by a protective volar splint for six weeks. Active motion exercise was started one week after surgery. All patients received hand therapy. Standard radiographs were obtained after six months and assessed for implant alignment, position of the screws, bone reaction and evidence of implant loosening (Figure 1).

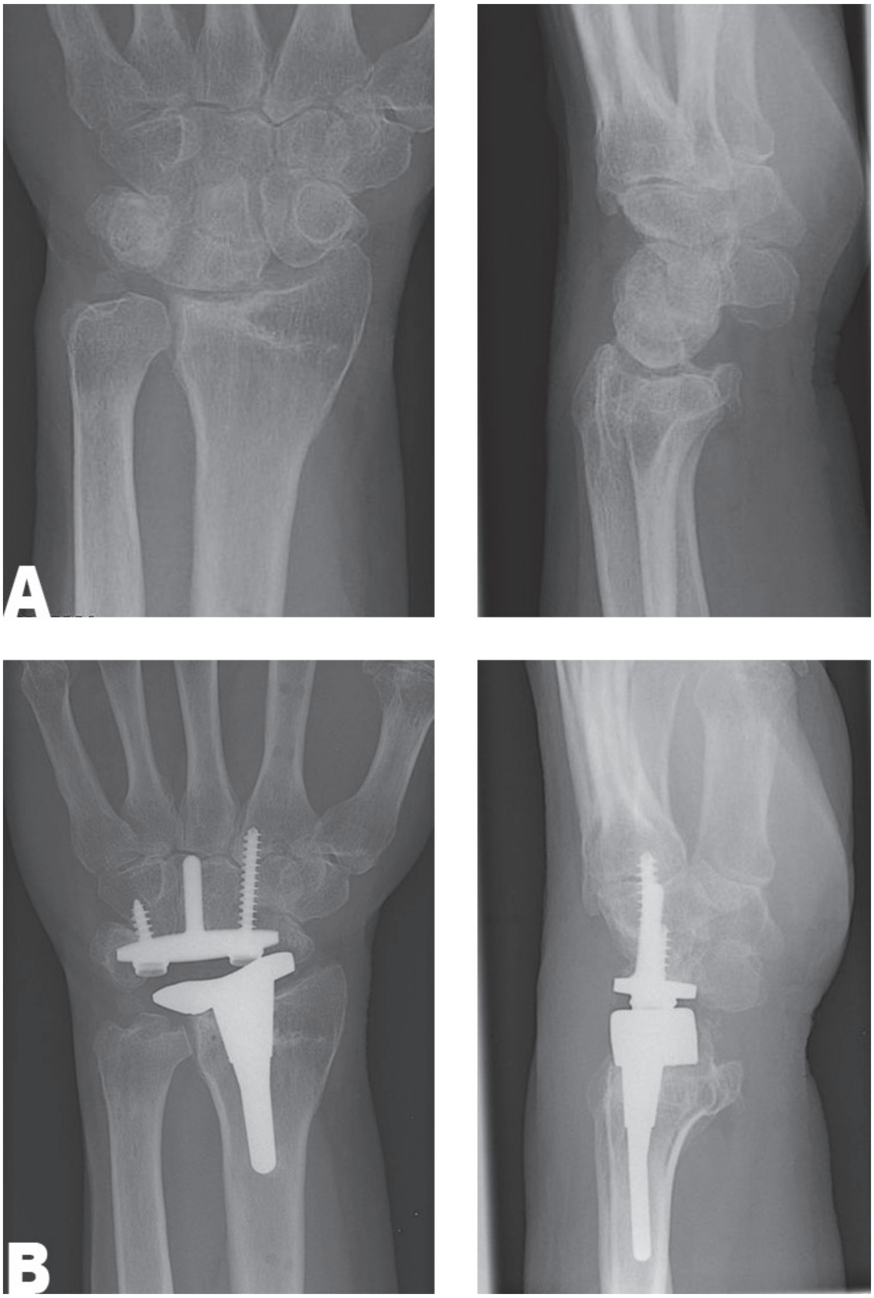

FIGURE 1. (A) Preoperative X-ray (PA and lateral view) of a patient with grade 4 osteoarthritis. **(B)** Postoperative X-ray (PA and lateral view) of the same patient 6 months after Universal 2 implant (Integra Life Sciences). PA: posteroanterior.

Short-term outcome assessment

A standardized outcome assessment protocol was applied to all wrist patients in our clinic. An independent hand therapist assessed them pre-operatively, and at 6 and 12 months after surgery. Range of motion of the wrist (flexion-extension and radial-ulnar deviation) was assessed with a handheld goniometer and grip strength with the JAMAR dynamometer. All patients were asked to complete the full Disability of the Arm Shoulder and Hand (DASH) questionnaire (Dutch Language Version) and VAS pain score (0-10) at each of the three time points.[16]

Additional outcome assessment

Between January and March 2011, all noninflammatory patients with a Universal 2 prosthesis that were implanted 12 months earlier were invited to our clinic for a number of additional assessments by an independent researcher. They were divided into two groups: 1) with a follow up of one to two years (mean 14 months (12-18months)) and 2) with a follow up of more than two years (mean 34 months (24-50 months)). To evaluate hand function, patients were asked about their working status and completed the DASH questionnaire and the Michigan Hand Questionnaire (MHQ) (Dutch Language Version). The MHQ is divided into 6 subscales, which include overall hand function, activities of daily living, work, pain, aesthetics and satisfaction.[17]

Range of motion (flexion-extension, radial-ulnar deviation and circumduction) of the affected wrist was assessed with a biaxial flexible electrogoniometer (Biometrics©: XM-65, Biometrics Ltd, Gwent, UK) using a protocol that has been reported to be accurate and reliable.[18] All patients were instructed to perform flexion-extension, radial-ulnar deviation, and circumduction of the wrist at a comfortable speed, and to focus on maximizing ROM.

Grip strength was assessed with the MIE pinch/grip analyzer (MIE, Medical Research, Leeds, UK), which was set at the same width as that of a JAMAR dynamometer in position 2. Patients were asked to perform maximum grip for 60 seconds. This method allows for assessment of mean force, peak grip strength and endurance.

Data collected with the flexible electrogoniometer and the MIE pinch/grip analyzer were processed with MATLAB 7.1 software. Variables derived from the output of the flexible electrogoniometer were flexion-extension arc, radial-ulnar deviation arc, and circumference of the circumduction. The mean force, peak force and the slope of the force time curve were extracted from the MIE grip/pinch analyzer output.

RESULTS

Table 1 shows the results of the short-term assessment and additional outcome assessments. Overall, after surgery, range of motion and grip strength did not change compared to preoperatively. However, DASH scores improved compared to preoperative values by 22.8 points at 1 follow up and 35.7 points after >2 years follow up. Mean VAS score one year after surgery improved with three points compared to the preoperative value on a scale of 0-10. No malalignment of the prosthesis, or periprosthetic osteolysis was observed when reviewing post-operative X-rays.

Four of the eleven patients that were additionally assessed were already retired before surgery. Preoperatively, three patients performed heavy manual labor. After surgery, one patient returned to work (nurse), one patient switched to deskwork and one patient was unable to work. Two patients did not work preoperatively and did not start working after surgery.

Complications

One patient fell on his wrist that led to an extension lag. Two patients developed De Quervain’s disease, which settled with a corticosteroid injection in the first extensor compartment. Four patients complained of volar wrist pain and needed excision of the pisiform bone. However, in one patient, this reduced grip strength that we could not explain. One patient fell on his wrist 6 months after surgery which resulted in extensionlag and pain on the ulnar side of the wrist. Therefore, a Darrach procedure was performed one year after initial surgery. Figure 2 shows the pre-operative X-rays and postoperative x-rays after Universal 2 and Darrach procedure, respectively. In another patient, the distal ulna was resected one month after surgery because of ulnar sided wrist pain. Ulnar pain persisted after surgery therefore it was decided to excise the pisiform bone three months later. An ulnar head prosthesis was inserted four months after because of persisting pain.

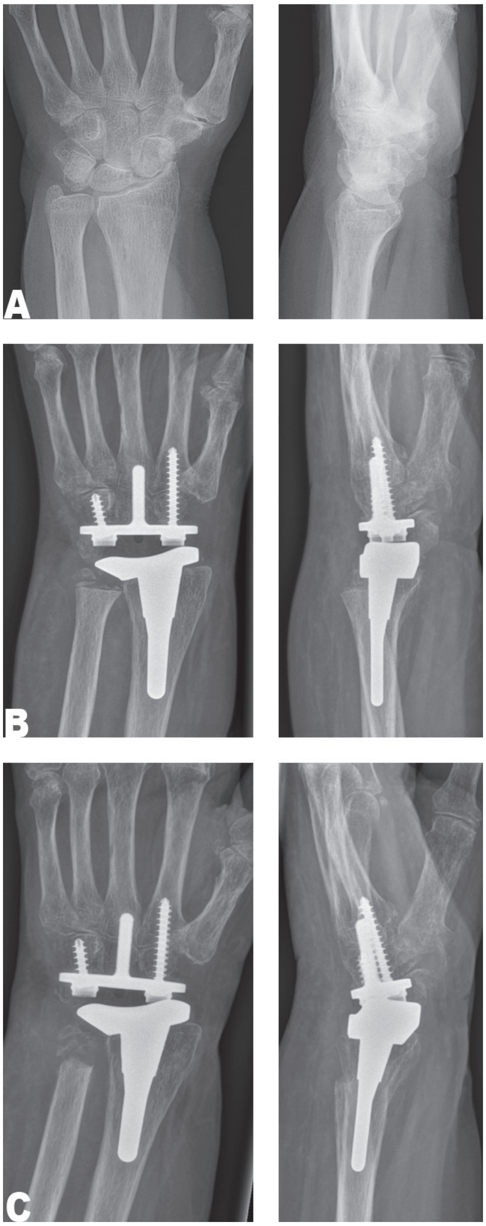

FIGURE 2. (A) Preoperative X-ray (PA and lateral view) of a patient with grade 4 osteoarthritis. **(B)** Postoperative X-ray (PA and lateral view) of the same patient after Universal 2 implant (Integra Life Sciences) with distal ulnar abutment, and **(C)** postoperative X-ray (PA and lateral view) of the same patient after Darrach procedure. PA: posteroanterior

TABLE 1. Results for range of motion, grip strength, and MHQ assessed during short-term outcome assessment and additional outcome assessment

	Short term outcome assessment			Additional outcome assessment	
	Pre-operative (n=18)	6 mo (n=14)	12 mo (n=12)	1-2 y (n=4)	≥2 y (n=8)
Active ROM	Mean (SD)	Mean (SD)	Mean (SD)	Median (range)	Median (range)
Flexion-extension arc (°)	71 (32)	66 (15)	71 (25)	84 (18-53)	74 (19-90)
Radial-ulnar deviation arc (°)	48 (22)	55 (17)	54 (18)	35 (29-39)	31 (21-49)
Circumference of circumduction (°)				129 (87-141)	91 (23-148)
Grip strength					
Peak force (kg)	11.5 (8)	9.6 (4)	11.9 (4)	11.2 (9.3-16.2)	12.5 (4-39.4)
Mean force (kg)				6.4 (3.8-10.4)	9.1 (2.9-31.4)
Slope				-0.4 (-1.1 to -0.13)	-0.7 (-1.54 to -0.27)
DASH score	*53.2 (20)*	*36.8 (24)*	*30.4 (20)*	*37.5 (18-53)*	*17.5 (3-34)*
VAS score (pain at rest)	*6 (1)*	*4 (2)*	*3 (3)*		
Michigan Hand questionnaire					
Overall hand function				60 (50-95)	55 (40-100)
Activities of daily living				75 (70-95)	83 (40-100)
Pain				35 (5-55)	37.5 (0-55)
Aesthetics				100 (75-100)	100 (81.3-100)
Satisfaction				75 (54.2-100)	54.2 (25-100)
Total score				66.1 (56.6-97.3)	71.5 (46.9-100)

DASH: disabilities of the arm, shoulder, and hand; ROM: range of motion; SD : standard deviation; VAS: visual analog scale.

DISCUSSION

There has been much debate over the last decade on whether patients with end stage wrist osteoarthritis are best treated with a wrist arthroplasty or arthrodesis. Previous case series focused on RA patients. Cavaliere and Chung [7] performed a systematic meta-analysis (503 total wrist arthroplasties versus 860 total wrist arthodeses) in RA patients and concluded that outcomes for total wrist fusion were comparable and possibly better than that for total wrist arthroplasty. However, their total wrist arthroplasty data mainly consisted of second and third generation total wrist prostheses (Meuli, Volz and Biaxial prostheses). Boekstyns [19] recently performed a systematic review on wrist arthroplasty in RA and PTOA patients. He concluded that more recent generations of implants provide improvement of function through pain reduction and preservation of mobility, despite methodological shortcomings in the reviewed studies. In addition, he concluded that more recent generation implants showed high survival rates (90-100%) at five year follow-up.

The newest - fourth generation - implants need less bone resection, screw fixation to the carpus, and are uncemented. Nydick et al.[20] found similar patient reported outcomes when comparing PTOA patients who received the Maestro prosthesis to PTOA patients with a total wrist arthrodesis. However, Adey et al.[4] reported substantial dysfunction after total wrist arthrodesis for PTOA patients. Additionally, 20 of their 22 patients would elect to undergo a procedure to regain wrist movement. Vicar et al.[21] found that RA patients who have had total wrist arthrodesis on one wrist and a total wrist arthroplasty on the other preferred the side with the arthroplasty.

Literature on the Universal 2 prosthesis showed conflicting and incomplete (i.e. missing pre-operative information) data on different outcome measures.[10-13] Comparison of our results with existing literature was therefore not possible. A couple of studies reported range of motion and functional outcome of the Universal 2 total wrist implant.[10-13] However, all of these studies were performed on a small patient group and almost exclusively in RA-patients. Reported postoperative range of motion ranged from 28 to 68° for flexion-extension, and 18° to 26° for radial-ulnar deviation. We found a slightly higher postoperative range of motion in our patients. DASH and Patient Rated Wrist Evaluation improved after an arthroplasty, but the DASH scores varied between 55.1 and 91 pre-operatively, and between 41.9 and 65 postoperatively.[10-13] We noted a 35-point improvement after more than two years.

The few studies on other fourth generation total wrist implants in PTOA patients demonstrated similar results to our study. Herzberg [22] (n=7), Boeckstyns et al.[23] (n= 15) and Nydick et al.[24] (n=13) all found preservation or a slight increase in range of motion and grip strength. Nydick et al.[24] also reported a postoperative DASH score of 33. Unfortunately, no preoperative patient reported outcome was available, so these results could not be compared to ours. Reigstad et al.[25] presented the one- to six-year outcomes of the third generation Motec total wrist arthroplasty in posttraumatic patients (n=30) and reported a 20-point improvement in DASH score, significantly improvement in VAS scores and preservation of wrist motion and grip strength.

Previous studies have shown that assessment of wrist circumduction provides a good representation of the capacity of the wrist.[18, 26, 27] Wrist circumduction combines flexion, extension, and radioulnar deviation, which are necessary for activities during daily living. No previous studies have reported wrist circumduction after a total wrist arthroplasty. We found that the circumference of circumduction in PTOA patients after arthroplasty was reduced compared to healthy wrists by 56%.[18]

A limitation of our study is the small number of patients. This is comparable to published literature and reflects the very small patient population. Another limitation is that follow-up was short. While our follow-up is sufficiently long to describe functional outcome, we cannot comment on long-term implant loosening, fracture, dislocation or failure. We did not have preoperative data on circumduction and MHQ scores. Furthermore, range of motion during additional assessment was assessed with flexible electrogoniometers compared to handheld goniometers during short-term outcome assessment. Therefore, differences in radial-ulnar deviation may be due to the assessment method or due to the small number of patients. This study did not have a randomly assigned control group, so we cannot comment on how the outcome would relate to alternative treatment, such as wrist arthrodesis.

It is not clear from literature what range of motion is needed for normal ADL function. Ryu et al.[28] concluded that most ADL can be performed with 40° flexion, 40° extension and 40° radial-ulnar deviation. However, Palmer et al.[29], found smaller values: 5° flexion, 30° extension, 10° radial deviation, and 15° ulnar deviation. Since we noted 74° flexion-extension and 31° radial-ulnar deviation after more than two years we conclude that the range of motion after a Universal 2 prosthesis is sufficient for ADL, as confirmed by the MHQ scores and improved DASH.

In conclusion, the Universal 2 Total wrist prosthesis could be considered in patients with end stage noninflammatory wrist osteoarthritis as an alternative to wrist arthrodesis, especially since the fourth generation of total wrist implants require less bone excision, leaving an arthrodesis after a failed arthroplasty as a salvage option. We found good results at follow-up. At present, not much is known about the long-term implant failure. Although results of the newest generation implants suggest significant improvement compared to older generation implants, longer follow-up periods are needed to determine their survival rate. A survival rate that is comparable to the survival rate of hip or knee implants would truly clear the way for wrist arthroplasty in PTOA patients. Future studies should therefore focus on a prospective design, a substantial sample size, and long term follow up.

REFERENCES

1. Sauerbier, M., et al., Surgical treatment possibilities of advanced carpal collapse (SNAC/SLAC wrist). Unfallchirurg, 2000. 103(7): p. 564-71.
2. Kobus, R.J. and R.H. Turner, Wrist arthrodesis for treatment of rheumatoid arthritis. J Hand Surg Am, 1990. 15(4): p. 541-6.
3. Rayan, G.M., et al., Functional assessment of bilateral wrist arthrodeses. J Hand Surg Am, 1987. 12(6): p. 1020-4.
4. Adey, L., D. Ring, and J.B. Jupiter, Health status after total wrist arthrodesis for posttraumatic arthritis. J Hand Surg Am, 2005. 30(5): p. 932-6.
5. De Smet, L. and J. Truyen, Arthrodesis of the wrist for osteoarthritis: outcome with a minimum follow-up of 4 years. J Hand Surg Br, 2003. 28(6): p. 575-7.
6. Barbier, O., et al., Long-term functional results of wrist arthrodesis in rheumatoid arthritis. J Hand Surg Br, 1999. 24(1): p. 27-31.
7. Cavaliere, C.M. and K.C. Chung, A systematic review of total wrist arthroplasty compared with total wrist arthrodesis for rheumatoid arthritis. Plast Reconstr Surg, 2008. 122(3): p. 813-25.
8. Ritt, M.J., et al., The early history of arthroplasty of the wrist. From amputation to total wrist implant. J Hand Surg Br, 1994. 19(6): p. 778-82.
9. Weiss, A.P., R.N. Kamal, and P. Shultz, Total wrist arthroplasty. J Am Acad Orthop Surg, 2013. 21(3): p. 140-8.
10. Ferreres, A., A. Lluch, and M. Del Valle, Universal total wrist arthroplasty: midterm follow-up study. J Hand Surg Am, 2011. 36(6): p. 967-73.
11. McCullough, M.B., B.D. Adams, and N.M. Grosland, Postoperative analysis of patients who received the Universal 2 total wrist implant system. J Appl Biomech, 2012. 28(4): p. 466-72.
12. Morapudi, S.P., et al., Total wrist arthroplasty using the Universal 2 prosthesis. J Orthop Surg (Hong Kong), 2012. 20(3): p. 365-8.
13. van Winterswijk, P.J. and P.A. Bakx, Promising clinical results of the universal total wrist prosthesis in rheumatoid arthritis. Open Orthop J, 2010. 4: p. 67-70.
14. Menon, J., Universal Total Wrist Implant: experience with a carpal component fixed with three screws. J Arthroplasty, 1998. 13(5): p. 515-23.
15. Adams, B.D., Total wrist arthroplasty. Tech Hand Up Extrem Surg, 2004. 8(3): p. 130-7.
16. Beaton, D.E., et al., Measuring the whole or the parts? Validity, reliability, and responsiveness of the Disabilities of the Arm, Shoulder and Hand outcome measure in different regions of the upper extremity. J Hand Ther, 2001. 14(2): p. 128-46.
17. Chung, B.T. and S.F. Morris, Reliability and Internal Validity of the Michigan Hand Questionnaire. Ann Plast Surg, 2013.
18. Singh, H.P., et al., Assessment of velocity, range, and smoothness of wrist circumduction using flexible electrogoniometry. J Hand Surg Am, 2012. 37(11): p. 2331-9.

19. Boeckstyns, M.E., Wrist arthroplasty--a systematic review. Dan Med J, 2014. 61(5): p. A4834.

20. Nydick, J.A., et al., Clinical outcomes of arthrodesis and arthroplasty for the treatment of posttraumatic wrist arthritis. J Hand Surg Am, 2013. 38(5): p. 899-903.

21. Vicar, A.J. and R.I. Burton, Surgical management of the rheumatoid wrist--fusion or arthroplasty. J Hand Surg Am, 1986. 11(6): p. 790-7.

22. Herzberg, G., Prospective study of a new total wrist arthroplasty: short term results. Chir Main, 2011. 30(1): p. 20-5.

23. Boeckstyns, M.E., G. Herzberg, and S. Merser, Favorable results after total wrist arthroplasty. Acta Orthop, 2013.

24. Nydick, J.A., et al., Clinical outcomes of total wrist arthroplasty. J Hand Surg Am, 2012. 37(8): p. 1580-4.

25. Reigstad, O., et al., Promising one- to six-year results with the Motec wrist arthroplasty in patients with post-traumatic osteoarthritis. J Bone Joint Surg Br, 2012. 94(11): p. 1540-5.

26. Ojima, H., et al., Dynamic analysis of wrist circumduction: a new application of the biaxial flexible electrogoniometer. Clin Biomech (Bristol, Avon), 1991. 6(4): p. 221-9.

27. Rawes, M.L., J.B. Richardson, and J.J. Dias, A new technique for the assessment of wrist movement using a biaxial flexible electrogoniometer. J Hand Surg Br, 1996. 21(5): p. 600-3.

28. Ryu, J.Y., et al., Functional ranges of motion of the wrist joint. J Hand Surg Am, 1991. 16(3): p. 409-19.

29. Palmer, A.K., et al., Functional wrist motion: a biomechanical study. J Hand Surg Am, 1985. 10(1): p. 39-46.

PART II

In vivo carpal kinematics

CHAPTER 5

Quantifying in vivo scaphoid, lunate, and capitate kinematics using four-dimensional computed tomography

M.E. Brinkhorst, M. Foumani, J.M. van Rosmalen, R.W. Selles, S.E.R. Hovius, S.D. Strackee, G.J. Streekstra

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ABSTRACT

Purpose: To establish a quantitative description of motion patterns and establish test-retest reliability of the four-dimensional CT when quantifying in vivo kinematics of the scaphoid, lunate, and capitate.

Methods: We assessed in vivo kinematics of both wrists of 20 healthy volunteers (11 men and 9 women) between the ages of 20 and 40 years. All volunteers performed active flexion-extension and radial-ulnar deviation with both wrists. To test for reliability, one motion cycle was rescanned for both wrists approximately 15 minutes after the first scan. The coefficient of multiple correlation was used to analyze reliability. When two motion patterns are similar, the coefficient of multiple correlation tends towards 1, whereas in dissimilar motion patterns, it tends towards 0. The root mean square deviation was used to analyze the total motion patterns variability between the two scans.

Results: Overall, mean or median coefficient of multiple correlations were higher than 0.86. The root mean square deviations were low and ranged from 1.17° to 4.29°.

Conclusions: This innovative non-invasive imaging technique can reliably describe in vivo carpal kinematics of uninjured wrists in healthy individuals. It provides us with a better understanding and reference values of carpal kinematics of the scaphoid, lunate, and capitate.

INTRODUCTION

The wrist is one of the most complex joints in the human body. Each carpal bone can perform multiplanar movements. To functionally stabilize the wrist, numerous strong ligaments interconnect wrist bones to surrounding structures, allowing them to function cohesively. By analyzing motion patterns of carpal bones quantitatively, we expect to be able to differentiate between normal and abnormal wrist kinematics which occur after ligament disruption.[1, 2]

Four-dimensional computed tomography (4D-CT) was introduced for the acquisition of dynamic 3D images of a moving wrist joint.[3-7] It yields a series of time-resolved 3D images, which allows studying individual wrist bone movements in a non-invasive way. Strengths of the 4D-CT method compared to other imaging methods for measurement of carpal kinematics, like 4D-RX [8, 9], is that it fits in the clinical workflow and that it needs limited acquisition time.

Until today, studies evaluated cadaveric wrists to describe radiocarpal kinematics.[4, 5, 7, 10] In addition, most studies did not quantitatively analyze the motion patterns of the carpal bones. For example, Zhao et al.[11] showed that the accuracy of this technique during in vitro simulated wrist movement was comparable to other image-based kinematic techniques like fluoroscopy, static biplane radiography, and CT. However, the latter measurements were performed in vitro. Consequently, quantitative 4D-CT-based data describing the in vivo motion patterns of the wrist joint and the associated reliability of 4D-CT are lacking. Such data is essential for comparison of motion patterns of the wrist of pathological wrists with those of healthy volunteers. Therefore, the purpose of this study was to establish a quantitative description of motion patterns and associated reliability of a 4D-CT analysis of in vivo scaphoid, lunate, and capitate kinematics in healthy adults.

MATERIALS AND METHODS

Participants

Subjects were included if they had no history of wrist injuries or heavy manual work and were aged between 20 and 40 years. Both wrists of 20 healthy volunteers (11 males and 9 females) with a mean age of 27 years (SD 4), were studied. This study was approved by the Medical Ethical Committee of our institute and informed consent was obtained from each subject.

Wrist motion guiding device

A custom-made motion guiding device was designed, implemented and, subsequently, used to minimize inter-individual differences in positioning the arm during scanning and guiding the hand and wrist during the 4D-CT recordings (Figure 1A). Participants were put in a prone position with one arm 180° abducted (Figure 1B). The forearm was placed in the motion guiding device with the elbow extended and the forearm fixed to a framework. Metacarpals were placed in a natural position on a handlebar that is attached to the framework. Subjects were instructed to lightly grab the handlebar while actively performing maximum flexion-extension motion or radial-ulnar deviation with their wrist.

4D-CT imaging protocol

A Brilliance 64-slice CT scanner (Philips Medical System; Best; The Netherlands) was used for 3D and 4D-CT acquisitions. To reconstruct the geometry of the carpal bones, a static CT image of the wrist was taken with the wrist in a neutral position. Static CT scans of the wrists were made at 120 kV and 75 mAs. The CT images were checked for gross pathology of the wrist, including possible internal derangement of carpal bones.

Subsequently, one flexion-extension or radial-ulnar deviation motion cycle was imaged in approximately 10 seconds with a 4D CT protocol. Collimation of the 4D scans was 64x0.625 mm, resulting in an axial field of view of 4 cm. Applied tube voltage and charge per time frame were 120 kV and 15 mAs, respectively. Voxel size of the static scan was 0.33x0.33x0.33 mm. Voxel size of a 4D frame was 0.49x0.49x0.62 mm. Sampling frequency was 2.5Hz (every 0.4 seconds), the exposure for each time frame time 0.27 seconds. Thirty different 3D time frames per complete motion cycle were collected with each 4D-CT scan.

Randomization was used to decide which wrist was scanned first. After both wrists were scanned, subjects were asked to leave the room. Then, to establish test-retest reliability, the subject was asked back and one motion cycle was rescanned for each wrist approximately 15 minutes after the first scan. Randomization was also used to decide which motion cycle (flexion-extension or radial-ulnar deviation) of a wrist was rescanned. When the right wrist was randomly assigned to repeat flexion-extension motion, the left wrist repeated radial-ulnar deviation motion.

B

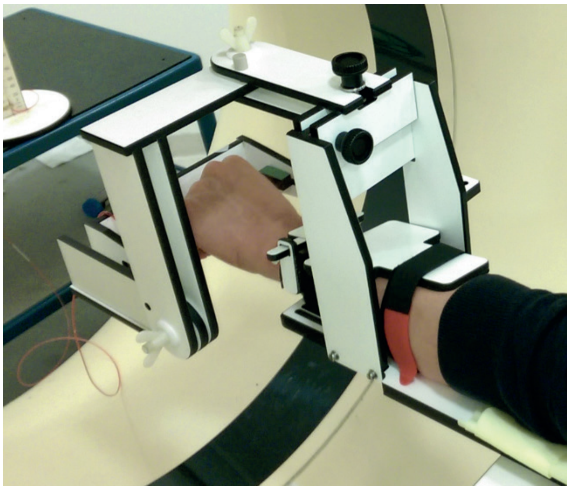

FIGURE 1 (A) Custom-made device to guide the hand and wrist during the 4D-CT recordings. (**B)** Positioning of a participant during 4D-CT recordings.

A total of 10 dominant wrists and 10 non-dominant wrists were rescanned for the flexion-extension motion cycle and a total of 10 dominant wrists and 10 non-dominant wrists were rescanned for the radial-ulnar deviation motion cycle to establish reliability. Data was saved and stored anonymized.

Segmentation, and estimation of translation and rotation of the carpal bones

After all anonymized data was collected, segmentation of the images was performed. The method of segmentation and estimation of translation and rotation of the radius and carpal bones used in the present study was first introduced by Carelsen [8] and Foumani.[9] In short, segmentation of the carpal bones and radius from the CT image was semi-automatically performed by a region-growing algorithm using custom-made software.[12] Only the static scan was segmented. Each scan consisted of 300-350 slices with 0.33 mm distance in between. To estimate rotation and translation of the individual bones relative to the neutral position, the segmented radius and carpal bones were registered to the corresponding bones in the volumes of the dynamic scan.

Kinematics

The scaphoid, lunate and capitate were analyzed to describe radiocarpal kinematics, since those are the key players in wrist joint function. To express various motion parameters of individual carpal bones, an anatomically-based radial coordinate system, described by Kobayashi et al.[13], was used (Figure 2). Coordinate axes of the scaphoid, lunate, and capitate were defined as being parallel to this radial coordinate system with the wrist in a neutral position. Furthermore, wrist motion was defined as the rotation of the capitate relative to the radius.[14, 15] Subsequently, flexion was defined as "+" and extension as a "-" rotation around the X-axis, radial deviation as a "+" and ulnar deviation as a "-" rotation around the Y-axis and pronation as a "-" and supination as a "+" rotation around the Z-axis.

Only rotational parameters of the scaphoid, lunate, and capitate were evaluated in this study since previous studies showed that translations of carpal bones were marginal.[15-17] To describe the rotational parameters, the helical axis and attitude vector were determined.[18] The helical axis, which is essentially the axis of rotation of a carpal bone during motion, was estimated for each time frame in a 4D-CT sequence from the previously determined neutral position and the position during motion. Subsequently, the attitude vector was defined by a multiplication of the amount of rotation around the helical axis and the unit vector of pointing in the direction of the helical axis. Eventually, rotation parameters in X-, Y- and Zdirection were estimated based on components of the attitude vector in the radial coordinate system.

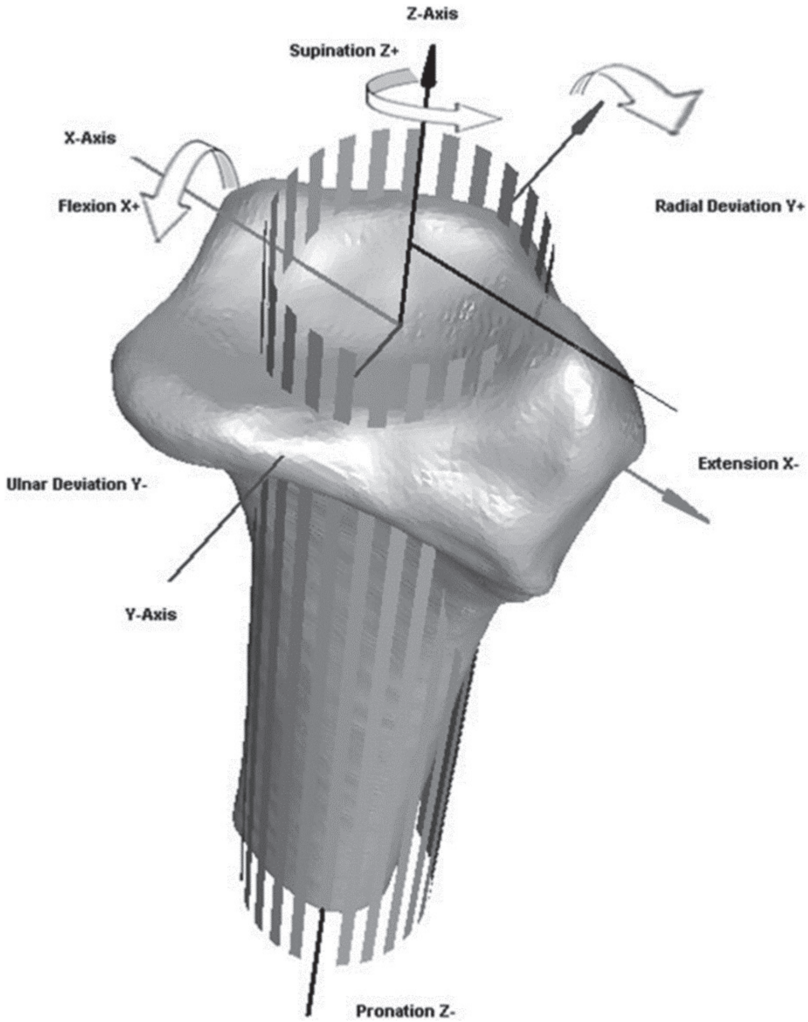

FIGURE 2. Anteroradial view of a right radius. Repositioning of the carpal bones is expressed in terms of an anatomically based coordinate system for the radius (9). The X-axis goes straight through the distal radioulnar joint towards the radial styolid androtation around the X-axis indicates flexion (+) or extension (-). The Y-axis is perpendicualr to the X-axis and rotation around the Y-axis indicates ulnar deviation (-) or radial deviation (+). The Z-axis is perpendicular to the X- and Y-ais and is based on the longitudinal axis of the radius. Rotation around the Z-axis indicates supination (+) or pronation (-). *Reprinted from Journal of Biomechanics, 42, Foumani, M., Strackee, S.D., Jonges, R., Blankevoort, L., Zwinderman, A.H., Carelsen, B., Streekstra, G.J., In-vivo three-dimensional carpal bone kinematics during flexion-extension and radio-ulnar deviation of the wrist: Dynamic motion versus step-wise static wrist positions, 2664-2671, Copyright (2009), with permission from Elsevier.*

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Statistical analysis

All complete motion cycles were linearly interpolated to obtain data at every 1° of radial wrist motion, in which global wrist motion was defined as degrees of capitate rotation around the X-axis during flexion-extension and Y-axis during radial-ulnar deviation. Primary outcome variables per carpal bone were defined as the X, Y, and Z rotational components per 1° of global wrist motion.

Test-retest reliability was calculated with the coefficient of multiple correlation (CMC), first described by Kadaba et al.[19], and the Root Mean Square Deviation (RMSD). The CMC was calculated to evaluate the similarity between two motion patterns. When two motion patterns are similar, the CMC tends towards 1, whereas in dissimilar waveforms, it tends towards 0. The CMC is defined mathematically as

$$CMC_i = \sqrt{\frac{\sum_{t=1}^{2}\sum_a (Y_{iat}-\bar{Y}_{it})^2/A}{\sum_{t=1}^{2}\sum_a (Y_{iat}-Y_i)^2/(2A-1)}}, \quad (1)$$

where CMC_i is the CMC value of test subject i, Y_{iat} is the helical rotation of test subject i at motion cycle t (t=1 or t=2) with a global wrist motion of a degrees, and A denotes the number of wrist motion angles in the summation. $\bar{Y}_{it}$ is defined as the average of the helical rotations for subject i at motion cycle t (i.e. $\bar{Y}_{it} = \frac{1}{A}\sum_a Y_{iat}$), and $\bar{Y}_i$ is the average of all helical rotations for subject i (i.e. $\bar{Y}_i = \frac{1}{2A}\sum_{t=1}^{2}\sum_a Y_{iat}$). In all summations with respect to the global wrist motion, only angles are included that were observed at both motion cycles for that specific subject.

The CMC value is related to several aspects of the data and the data collection procedure. By removing the vertical offset, inconsistencies in wrist placement during scanning and segmentation of the individual bones is minimalized. Therefore, individual CMC values were calculated with and without correction for vertical offset between motion cycles.[20] The correction for offset consisted of subtracting $\bar{Y}_{it}$ from all observed Y_{iat} before calculating the result of Equation 1. The mean and standard deviation of the individual CMC values, with and without correction for offset, were reported for all rotations per carpal bone. If the CMC was not a real number for one or more test subjects, due to a negative value inside the square root, the median and interquartile range were reported instead.

To analyze total waveform variability present between test and retest, the RMSD was used. RMSD represents the sample standard deviation of the differences in the measured angles between the first and the repeated motion. It is calculated by taking the root of the mean squared difference between the two motion cycles. Statistical analyses were performed using SPSS version 21.

RESULTS

Check for wrist pathology

No pathology was observed in the static CT-scans of the wrists. Consequently, the total of 20 wrists could be used for further evaluation.

Carpal kinematics

The lunate and scaphoid both flex when the wrist is flexed and both extend when the wrist is extended (figure 3, video 1). The lunate, scaphoid, and capitate deviate ulnar during flexion of the wrist and all deviate radial when the wrist is extended. During radial-ulnar deviation of the wrist, the lunate and scaphoid extend when the wrist is ulnar deviated and flex when the wrist is radial deviated (figure 4, video 2).

Test-retest reliability

Overall, median or mean CMC were larger than 0.77 except for the flexion-extension pattern of the capitate during radial-ulnar deviation of the wrist (Table 1). After the offset was removed, median or mean CMC improved (range 0.86 – 1). RMSD's during flexion and extension of the wrist were maximally in the order of 3-4 degrees (Table 2).

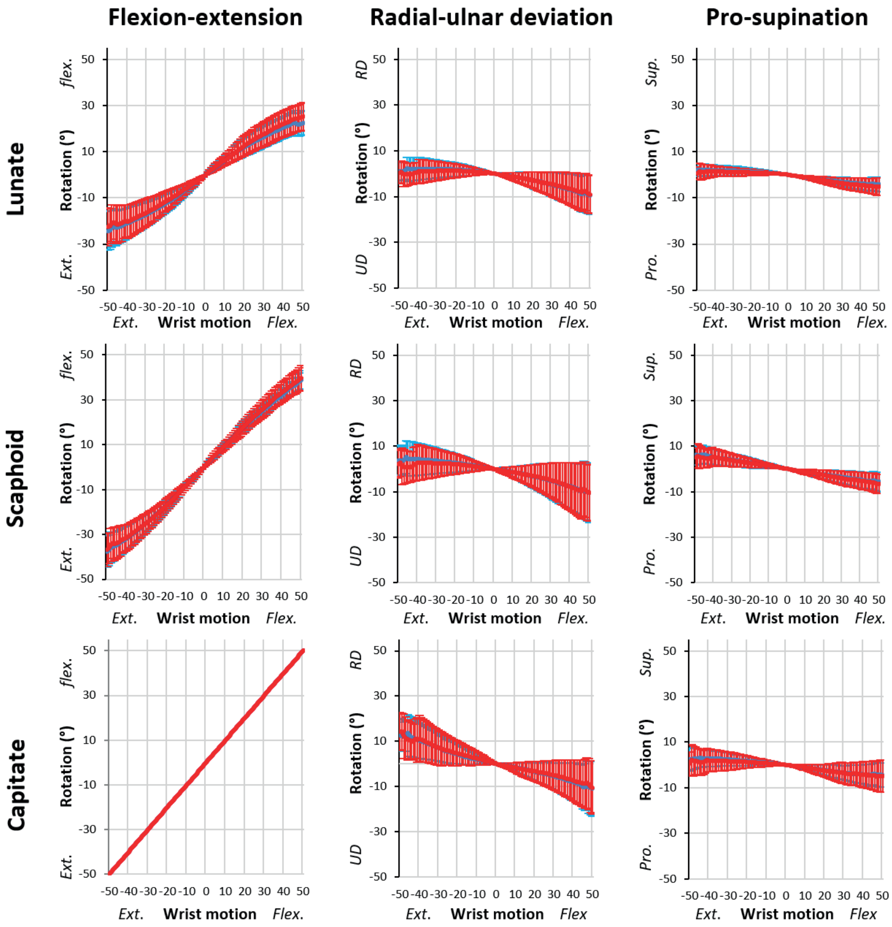


FIGURE 3. Comparison of the first scan (light blue) and the repeated scan (red) motion patterns in healthy volunteers during flexion-extension of the wrist. Mean and standard deviations of flexion-extension, radial-ulnar deviation and pro-supination of the lunate, scaphoid and capitate are plotted for every degree of wrist motion. Flexion-extension motion of the capitate is presented as a straight red line as the flexion-extension motion of the capitate was used to define the global wrist motion. Ext. extension, Flex. flexion, Pro. pronation, Sup. supination, UD ulnar deviation, RD radial deviation

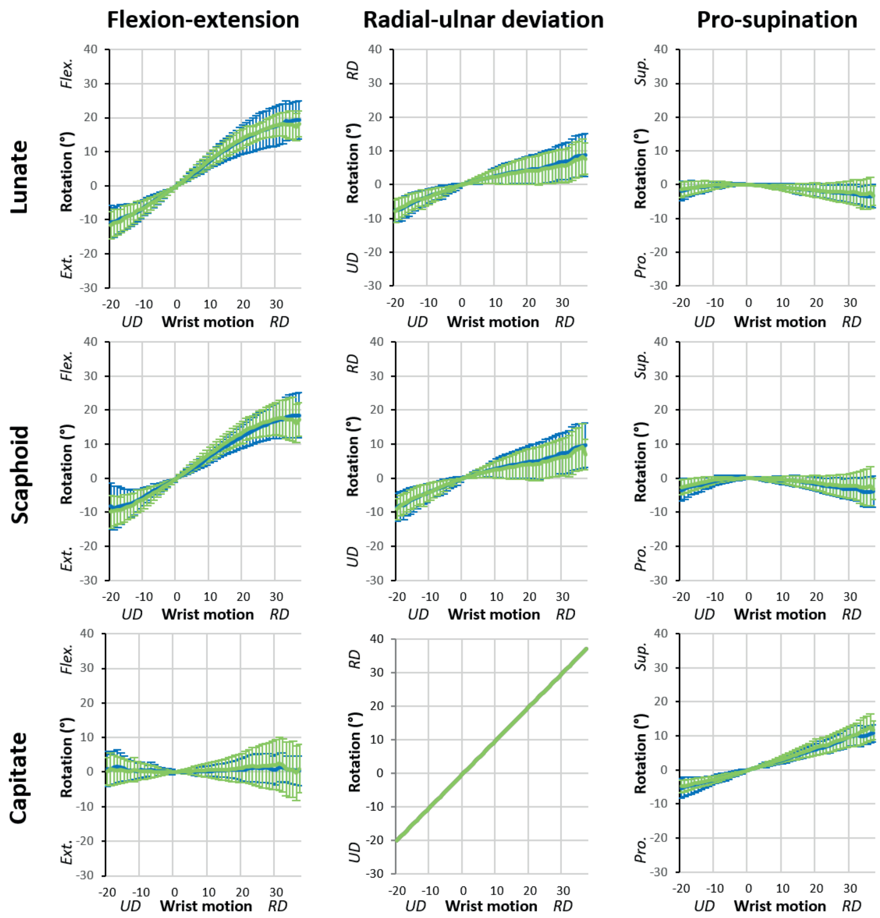


FIGURE 4. Comparison of the first scan (blue) and the repeated scan (light green) motion patterns in healthy volunteers during radial-ulnar deviation of the wrist. Mean and standard deviations of flexion-extension, radial-ulnar deviation and pro-supination of the lunate, scaphoid and capitate are plotted for every degree of wrist motion. Radial-ulnar deviation motion of the capitate is presented as a straight green line as the flexion-extension motion of the capitate was used to define the global wrist motion. Ext. extension, Flex. flexion, Pro. pronation, Sup. supination, UD ulnar deviation, RD radial deviation.

TABLE 1. Mean and standard deviation of the individual coefficient of multiple correlation (CMC) values, with and without correction for offset, for all rotations per carpal bone

CMC	Lunate	Scaphoid	Capitate
	Raw		
Flexion-extension wrist			
Flexion-extension	0.99 ± 0.01	1 ± 0.003	-
Radial-ulnar deviation	0.99 ± 0.23	0.95 ± 0.08	0.97 (0.90-0.99)
Pro-supination	0.93 ± 0.11	0.92 ± 0.16	0.84 (0.42-0.95)
Radial-ulnar deviation wrist			
Flexion-extension	0.97 ± 0.02	0.94 ± 0.06	0.77 (NA* – 0.86)
Radial-ulnar deviation	0.95 ± 0.09	0.93 ± 0.10	-
Pro-supination	0.84 ± 0.19	0.86 (0.71-0.96)	0.97 ± 0.03
	Offset removed		
Flexion-extension wrist			
Flexion-extension	0.99 ± 0.01	1.00 ± 0.003	-
Radial-ulnar deviation	0.91 ± 0.21	0.96 ± 0.07	0.98 (0.95-0.99)
Pro-supination	0.95 ± 0.09	0.95 ± 0.08	0.86 (0.57-0.98)
Radial-ulnar deviation wrist			
Flexion-extension	0.98 ± 0.02	0.96 ± 0.04	0.86 (0.58-0.90)
Radial-ulnar deviation	0.96 ± 0.09	0.95 ± 0.09	-
Pro-supination	0.89 ± 0.154	0.94 (0.84-0.97)	0.98 ± 0.01

The median and interquartile range are reported when the CMC was not a real number for one or more test subjects.

TABLE 2. Root mean square deviations (RMSD) of wrist kinematics between two repeated wrist motion cycles

	Lunate	Scaphoid	Capitate
Flexion-extension wrist			
Flexion-extension	3.16°	2.74°	-
Radial-ulnar deviation	1.51°	1.85°	3.01°
Pro-supination	1.17°	1.41°	3.19°
Radial-ulnar deviation wrist			
Flexion-extension	3,37°	4.29°	3.67°
Radial-ulnar deviation	1.62°	2.09°	-
Pro-supination	1.25°	1.73°	1.90°

DISCUSSION

In the present study, in vivo carpal kinematics of the scaphoid, lunate and capitate in 20 healthy volunteers were assessed during flexion-extension and radial-ulnar deviation motion of the wrist with a dynamic 4D-CT imaging method. We found 4D-CT assessment of the wrist to be reliable, with overall mean and median coefficients of multiple correlations (CMCs) higher than 0.86 and RMSD's between 1.17° and 4.29°.

In the past, static images were used to detect morphologic differences, although joint motion is an essential part of diagnosing joint pathologies. A number of authors have described CT techniques to image and analyze the 3D kinematics of carpal bones. Most authors used in vitro models in which only one wrist was scanned.[4, 5, 7] Other authors used a step-wise motion of the wrist to reconstruct the total kinematics during full motion.[17, 21, 22] This stepwise technique provides an approximation of the true in-vivo kinematics of the carpal bones. In wrists without any pathology, no significant differences were found between step-wise and dynamic techniques.[8, 9] However, in a pathological wrist, such as in individuals with a scapholunate ligament (SLL) injury, abrupt changes in kinematics can easily be missed.

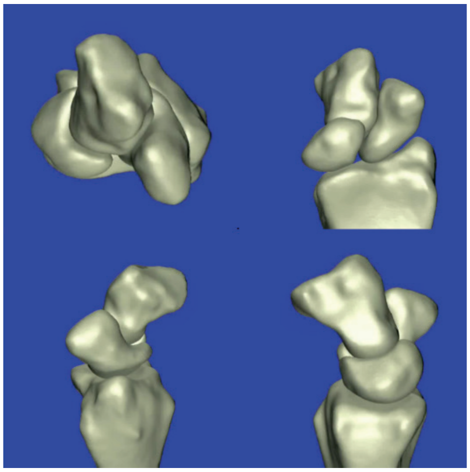
In the last years, various dynamic imaging techniques enabled acquiring real-time functional images. Techniques such as sonography, MRI, and fluoroscopy are presented in the literature, however, all with specific advantages and limitations.[23-26] Sonography enables us to image joints and ligaments during activities, but bony structures cannot be visualized. Magnetic resonance imaging (MRI) provides good images of soft-tissue structures such as ligaments, but dynamic use is difficult as a result of low spatial and temporal resolution. Fluoroscopy provides dynamic image acquisition but produces images that show overlapping carpal bones when assessing a wrist. Therefore, CT images combined with 4D rotational X-ray was proposed as a method for dynamic imaging of the wrist joint.[8, 9] A drawback of this method is that it requires multiple cyclic motions of the hand to obtain 4D images, which might be a problem for patients and may introduce artifacts if the different motion cycles are not consistent. True 4D imaging with CT (i.e., 4D-CT) solves the abovementioned problems of other dynamic imaging techniques for the wrist joint.

There are several limitations to our study. First is that he sample was of our study was relatively small. However, it is thus far the largest group of uninjured in vivo wrists that has tried establish a quantitative description of motion patterns and study test-retest reliability using the dynamic 4D CT method. Second, It was assumed that all wrists were uninjured and "normal" after medical history, physical examination and Beighton scores were taken. Nevertheless, disorders or congenitally different shapes of the carpal bones that might affect the findings were not ruled out. Third, we did not study a possible relationship between carpal bone morphology and carpal kinematics. However, van de Giessen et al.[27] found that there is a wide range of lunate shapes instead of just five. Because of their findings and our small group of participants it was decided not to investigate the influence of bone morphology on carpal kinematics.

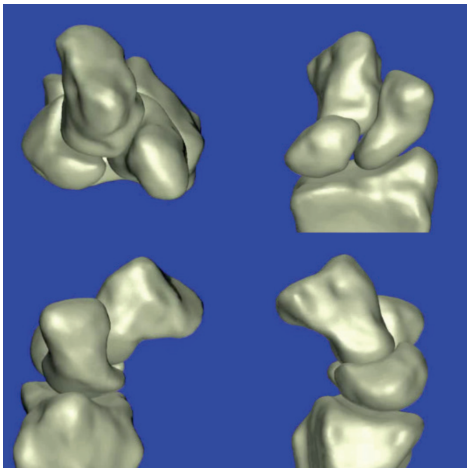
Our study used an in vivo and dynamic CT technique in which a subject performed only one motion cycle. Repeated measurements to test test-retest reliability showed CMC values tending towards 1. This indicates that there is only a slight variability in measurements among participants. CMC values of the scaphoid and lunate kinematics were between 0.84 and 1. The CMC value of the capitate were slightly lower (lowest 0.77). However, clinically, the kinematics of the capitate are less important in patients with specific wrist pathology like scapholunate ligament injury. RMSD's were between 1.17° and 4.29°, which indicates that there is not much variability between the waveform of the first and repeated scan. For example, the lowest RMSD was 1.17° for the pro-supination of the lunate during flexion-extension of the wrist. The flexion-extension motion of the lunate, scaphoid, and capitate showed to have the largest variability in motion pattern during flexion-extension and radial-ulnar deviation of the wrist when comparing the first and repeated motion.

In conclusion, this study yields a unique data set of in vivo motion patterns in the wrist joint that describes the kinematics of the scaphoid, lunate, and capitate and its reliability in detail. This data set provides a valuable reference for future clinical studies with 4D-CT.

APPENDICES



VIDEO 1: 4D-CT Video of the radius, scaphoid, lunate and capitate while flexion-extension is performed. Upper left: transversal view, upper right: anterior coronal view, left bottom: radial sagittal view, right bottom: ulnar sagittal view.



VIDEO 2: 4D-CT Video of the radius, scaphoid, lunate and capitate while radial-ulnar deviation is performed. Upper left: transversal view, upper right: anterior coronal view, left bottom: radial sagittal view, right bottom: ulnar sagittal view.

REFERENCES

1. Demehri S, Hafezi-Nejad N, Morelli JN, Thakur U, Lifchez SD, Means KR, et al. Scapholunate kinematics of asymptomatic wrists in comparison with symptomatic contralateral wrists using four-dimensional CT examinations: initial clinical experience. Skeletal Radiol. 2016; 45(4):437-446.
2. Demehri S, Hafezi-Nejad N, Thakur U, Morelli JN, Lifchez SD, Means KR, et al. Evaluation of pisotriquetral motion pattern using four-dimensional CT: initial clinical experience in asymptomatic wrists. Clin Radiol. 2015; 70(12):1362-1369.
3. Choi YS, Lee YH, Kim S, Cho HW, Song HT, Suh JS. Four-dimensional real-time cine images of wrist joint kinematics using dual source CT with minimal time increment scanning. Yonsei Med J. 2013; 54(4):1026-1032.
4. Leng S, Zhao K, Qu M, An KN, Berger R, McCollough CH. Dynamic CT technique for assessment of wrist joint instabilities. Med Phys. 2011; 38 Suppl 1:S50.
5. Mat Jais IS, Tay SC. Kinematic analysis of the scaphoid using gated four-dimensional CT. Clin Radiol. 2017; 72(9):794 e791-794 e799.
6. Shores JT, Demehri S, Chhabra A. Kinematic "4 Dimensional" CT Imaging in the Assessment of Wrist Biomechanics Before and After Surgical Repair. Eplasty. 2013; 13:e9.
7. Tay SC, Primak AN, Fletcher JG, Schmidt B, Amrami KK, Berger RA, et al. Four-dimensional computed tomographic imaging in the wrist: proof of feasibility in a cadaveric model. Skeletal Radiol. 2007; 36(12):1163-1169.
8. Carelsen B, Jonges R, Strackee SD, Maas M, van Kemenade P, Grimbergen CA, et al. Detection of in vivo dynamic 3-D motion patterns in the wrist joint. IEEE Trans Biomed Eng. 2009; 56(4):1236-1244.
9. Foumani M, Strackee SD, Jonges R, Blankevoort L, Zwinderman AH, Carelsen B, et al. In-vivo three-dimensional carpal bone kinematics during flexion-extension and radio-ulnar deviation of the wrist: Dynamic motion versus step-wise static wrist positions. J Biomech. 2009; 42(16):2664-2671.
10. Mat Jais IS, Liu X, An KN, Tay SC. A method for carpal motion hysteresis quantification in 4-dimensional imaging of the wrist. Med Eng Phys. 2014.
11. Zhao K, Breighner R, Holmes D, 3rd, Leng S, McCollough C, An KN. A technique for quantifying wrist motion using four-dimensional computed tomography: approach and validation. J Biomech Eng. 2015; 137(7).
12. Dobbe JG, Strackee SD, Schreurs AW, Jonges R, Carelsen B, Vroemen JC, et al. Computer-assisted planning and navigation for corrective distal radius osteotomy, based on pre- and intraoperative imaging. IEEE transactions on bio-medical engineering. 2011; 58(1):182-190.
13. Kobayashi M, Berger RA, Nagy L, Linscheid RL, Uchiyama S, Ritt M, et al. Normal kinematics of carpal bones: a three-dimensional analysis of carpal bone motion relative to the radius. J Biomech. 1997; 30(8):787-793.
14. de Lange A, Kauer JM, Huiskes R. Kinematic behavior of the human wrist joint: a roentgen-stereophotogrammetric analysis. J Orthop Res. 1985; 3(1):56-64.
15. Neu CP, Crisco JJ, Wolfe SW. In vivo kinematic behavior of the radio-capitate joint during wrist flexion-extension and radio-ulnar deviation. J Biomech. 2001; 34(11):1429-1438.

16. Kaufmann R, Pfaeffle J, Blankenhorn B, Stabile K, Robertson D, Goitz R. Kinematics of the midcarpal and radiocarpal joints in radioulnar deviation: an in vitro study. J Hand Surg Am. 2005; 30(5):937-942.

17. Wolfe SW, Neu C, Crisco JJ. In vivo scaphoid, lunate, and capitate kinematics in flexion and in extension. J Hand Surg Am. 2000; 25(5):860-869.

18. Woltring HJ. 3-D attitude representation of human joints: a standardization proposal. J Biomech. 1994; 27(12):1399-1414.

19. Kadaba MP, Ramakrishnan HK, Wootten ME, Gainey J, Gorton G, Cochran GV. Repeatability of kinematic, kinetic, and electromyographic data in normal adult gait. J Orthop Res. 1989; 7(6):849-860.

20. Roislien J, Skare O, Opheim A, Rennie L. Evaluating the properties of the coefficient of multiple correlation (CMC) for kinematic gait data. J Biomech. 2012; 45(11):2014-2018.

21. Crisco JJ, McGovern RD, Wolfe SW. Noninvasive technique for measuring in vivo three-dimensional carpal bone kinematics. J Orthop Res. 1999; 17(1):96-100.

22. Moojen TM, Snel JG, Ritt MJ, Venema HW, Kauer JM, Bos KE. In vivo analysis of carpal kinematics and comparative review of the literature. J Hand Surg Am. 2003; 28(1):81-87.

23. Rimondi E, Moio A, Busacca M, Tognetti A, Nigrisoli M, Tigani D, et al. Significance of computerized tomography in the diagnosis of post-traumatic proximal carpal instability. Radiol Med. 1998; 96(3):190-197.

24. Sulkers GS, Schep NW, Maas M, van der Horst CM, Goslings JC, Strackee SD. The diagnostic accuracy of wrist cineradiography in diagnosing scapholunate dissociation. J Hand Surg Eur Vol. 2013.

25. Weiss AP, Akelman E, Lambiase R. Comparison of the findings of triple-injection cinearthrography of the wrist with those of arthroscopy. J Bone Joint Surg Am. 1996; 78(3):348-356.

26. Zanetti M, Bram J, Hodler J. Triangular fibrocartilage and intercarpal ligaments of the wrist: does MR arthrography improve standard MRI? J Magn Reson Imaging. 1997; 7(3):590-594.

27. van de Giessen M, Foumani M, Streekstra GJ, Strackee SD, Maas M, van Vliet LJ, et al. Statistical descriptions of scaphoid and lunate bone shapes. J Biomech. 2010; 43(8):1463-1469.

CHAPTER 6

Four-dimensional CT analysis of carpal kinematics: The effect of gender and hand-dominance

M.E. Brinkhorst, M. Foumani, J.M. van Rosmalen, R.W. Selles,
S.E.R. Hovius, S.D. Strackee, G.J. Streekstra

In submission

ABSTRACT

Purpose: Wrist pathology is often diagnosed by using the contralateral wrist as a comparison of baseline motion and strength. However, recent range of motion studies suggest that females have different carpal motion patterns compared to males and that the dominant carpal bones have different motion patterns. The purpose of this study is to evaluate the effect of gender and hand dominance on in vivo kinematics of the scaphoid, lunate and capitate using four-dimensional computed tomography (4D-CT) analysis in healthy uninjured volunteers.

Methods: In this prospective study, both wrist of 20 uninjured Caucasian volunteers (11 men and 9 women) were assessed using 4D-CT during active flexion-extension and radial-ulnar deviation. A linear mixed model was used to compare the carpal motion patterns. Gender had no influence on carpal kinematics.

Results: Hand-dominance in males did have a significant effect on carpal kinematics. During flexion-extension of the male wrist, more radial-ulnar deviation of the lunate, scaphoid and capitate of the non-dominant hand was seen. During radial-ulnar deviation of the male wrist, radial-ulnar deviation and pro-supination of the lunate was more in the dominant hand.

Conclusions: This study provides a better understanding of carpal kinematics and the effect of gender and hand-dominance on the scaphoid, lunate and capitate in uninjured wrists.

INTRODUCTION

Diagnosis of ligament pathology in the wrist can be difficult due to poor understanding of carpal kinematics, inconsistencies in the physical examination and limited value of current imaging methods.[1, 2] Posture and stability of the carpal bones in uninjured wrists are maintained through the shape of the carpal bones, articulation with other bones, intercarpal ligaments and axial load. This stability may be disturbed due to ligament dysfunction resulting in a change of motion patterns of the carpal bones.[3] Disruption of the scapholunate ligament is one of the most frequently seen causes of carpal instability.[4] When left untreated it may lead to progressive secondary osteoarthritis called scapholunate advanced collapse (SLAC). Techniques that are used to diagnose ligament injuries and associated carpal instability are specific radiographs, like the clenched fist view, cineradiography, computed tomography (CT) and magnetic resonance imaging (MRI). For plain or stress radiographs, there is no strong evidence available on accuracy in the detection of ligamentous tears (sensitivity 57%, specificity 94%).[5] When plain radiographs are normal or inconclusive sometimes the MRI is used, it however has a sensitivity of 11% and specificity of 30%.[6, 7] Radiographs and MRI scans are both static modalities and therefore may lack specificity for diagnosing carpal instabilities.[6, 8] Cineradiography makes dynamic assessment of the wrist possible. However, the 2D nature of this method limits it to diagnose complex pathologies like carpal instabilities.[9] The gold standard for diagnosing ligament injuries is wrist arthroscopy, this is however an invasive technique. To diagnose and treat pathologies of the wrist it is important to understand the kinematics of the healthy wrist.

Early studies investigated normal wrist kinematics.[10-12] In those studies various imaging methods were used, each with specific strengths and limitations.[2] Over the course of time the use of static 2D imaging methods such as planar radiographs to study kinematics was replaced by three-dimensional (3D) imaging methods such as MRI or CT.[13-17] With these techniques 3D images at multiple poses can be acquired to provide an approximation of the true continuous carpal kinematics during a dynamic activity. Currently, dynamic scanning technologies such as four-dimensional (4D) (3D+time) X-ray (RX), 4D computed tomography (4D-CT) and 4D Magnetic Resonance Imaging (4D-MRI) are now available.[18-21] The introduction of the 4D-CT allows us to study individual wrist bone movements in a non-invasive and in a true dynamic way.[20] 4D-CT can reliably describe in vivo carpal kinematics of uninjured wrists.[22]

Wrist pathology is often diagnosed by using the contralateral wrist as a comparison of baseline motion and strength. However, current literature on range-of-motion of the wrist suggests that females have different carpal motion patterns compared to males and that the non-dominant carpal bones have a different motion pattern than the carpal bones of the dominant side.[23] In these studies a detailed analysis of the dependency of carpal kinematics on gender and hand dominance is lacking. The objective of this study was therefore to evaluate the effect of gender and hand dominance on in vivo kinematics of the scaphoid, lunate and capitate using 4D-CT analysis in healthy uninjured participants. We hypothesize that the carpal kinematics of the scaphoid, lunate and capitate between the dominant and non-dominant hand, and between males and females do not differ significantly.

MATERIALS AND METHODS

Participants

Participants were excluded if they had exam consistent with wrist injury or heavy manual work and were aged between 20 and 40 years. Since the scaphoid experiences more rotation during radial-ulnar motion in hypermobile patients [24], all participants with a history of hypermobility (see below) were excluded. Both wrists of 11 males with a mean age of 27 years (SD 5), and 9 females with a mean age of 28 years (SD 3) were studied. Maximum active range of motion (ROM) was assessed with a handheld goniometer. Our prospective study was approved by the Medical Ethical Committee and written informed consent was obtained from each volunteer.

Hand hypermobility and range of motion assessment

The Beighton score was used to assess hypermobility. This score is frequently used as a screening tool for the adult population.[25] The test requires the performance of four passive bilateral maneuvers and one active unilateral maneuver of several joints in the human body. Scores can range from 0 (unable to execute any of the tests) to 9 (able to execute all tests). A maximal score of 9 was considered as hyper laxity, whereas a score ≥4 was used as a clinical diagnosis of hypermobility. Patients in this study were excluded if the Beighton score was ≥4. Range of motion (ROM) of both wrists was assessed with a handheld goniometer. The proximal arm of the goniometer was aligned with radius and the distal arm positioned over the third metacarpal. Participants were asked to perform maximum flexion-extension or radial-ulnar deviation with their wrists while holding their hand gently clenched. Both wrists were assessed.

4D-CT scanning and kinematic assessment protocol

Participants were put in a prone position with one arm 180° abducted overhead, the forearm was placed in custom-made motion guiding device with the elbow extended and the forearm fixed to a framework to guide the hand and wrist during the 4D-CT recordings. Participants were instructed to lightly grab the handlebar while actively performing maximal extension to maximal flexion and maximal ulnar deviation to maximal radial deviation. Randomization was used to decide which wrist was scanned first.

A static 3D-CT scan (120kV, 75 mAs) in neutral position to segment the bony geometry was taken with the Brilliance 64-slice CT scanner (Philips Medical System; Best; The Netherlands). The neutral position was defined as the position in which the third metacarpal bone was oriented along the axis of the lower arm. Subsequently, one flexion-extension or radial-ulnar deviation motion cycle was made in approximately 10 seconds with a 4D CT protocol (120 kV, 30mAs, 64 slices x 0.625mm, axial field of view 4cm, in plane field of view 154x154 mm, rotation time 0.4s). The 4D CT scan resulted in a sequence of 30 3D images each with dimensions of 512x512x64 voxels. During the dynamic sequences all carpal bones that were analyzed and the distal part of the radius were completely visible in all volumes. Segmentation of the carpal bones and distal radius from the static CT image was performed by a region-growing algorithm, which was first introduced and described by Carelsen et al [26] and Foumani et al.[21] The segmented bones were registered to the corresponding bones in the volumes of the dynamic scan to estimate rotation and translation of each individual bone. To this end we used a stack of double contours from the static 3D image as bone boundary characterization: one outside the bone boundary (low intensity) and one on a short distance within the bone on the hard rim (high intensity). The double contour of the boundary is registered to each 3D time frame in the 4D image sequence to obtain an accurate estimation of all translational and rotational parameters. Figure 1 shows a sequence of 3 images generated after segmentation of the 4D CT scan.

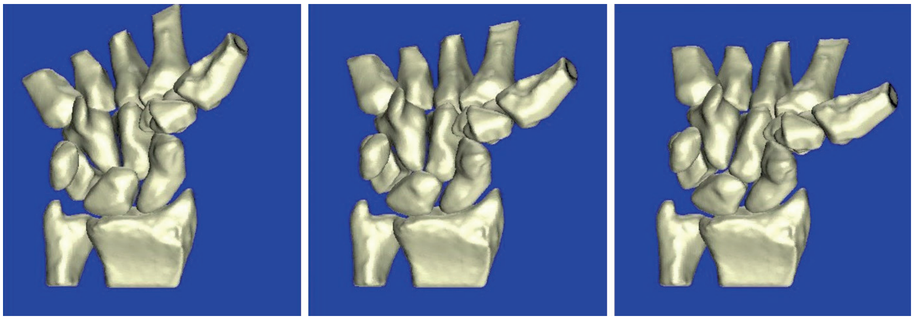


FIGURE 1. Sequence of three images generated after segmentation of the 4D-CT scan of the right wrist (volar view). The left images is produced with the wrist in ulnar deviation, the middle images is produced when the wrist is in a neutral position and the right images is produced with the wrist radial deviation.

Global wrist motion was defined as the motion (in degrees) of the capitate relative to the radius, with 0° taken from the static scan with the wrist in a neutral position. To quantitatively asses the kinematics of the carpal bones, an anatomically-based radial coordinate system, described by Kobayashi et al [15] was used (Figure 2). Flexion was defined as "+" and extension as a "-" rotation around the X-axis, radial deviation as a "+" and ulnar deviation as a "-" rotation around the Y-axis and pronation as a "-" and supination as a "+" rotation around the Z-axis. Since previous studies showed that translations of carpal bones were marginal, only rotational parameters of the carpal bones were evaluated.[27-29] The precision of the angle measurements in a 4D-CT scan with our system is in the order of 0.5mm.[30]

Statistical analysis

Linear mixed models were used to compare the carpal motion patterns of dominant wrists with non-dominant wrists and carpal motion patterns of males with those of females. The analysis focused equally on gender and hand dominance. Global wrist motion was entered as a repeated effect using an Autoregressive-Moving-Average (ARMA) (1,1) covariance structure to account for correlations between observations within a motion cycle. Random intercepts and slopes of global wrist motion were used to account for the within-subject correlations. This means that the model assumes that the level of the carpal motion pattern and its trend with respect to global wrist motion can vary between participants.

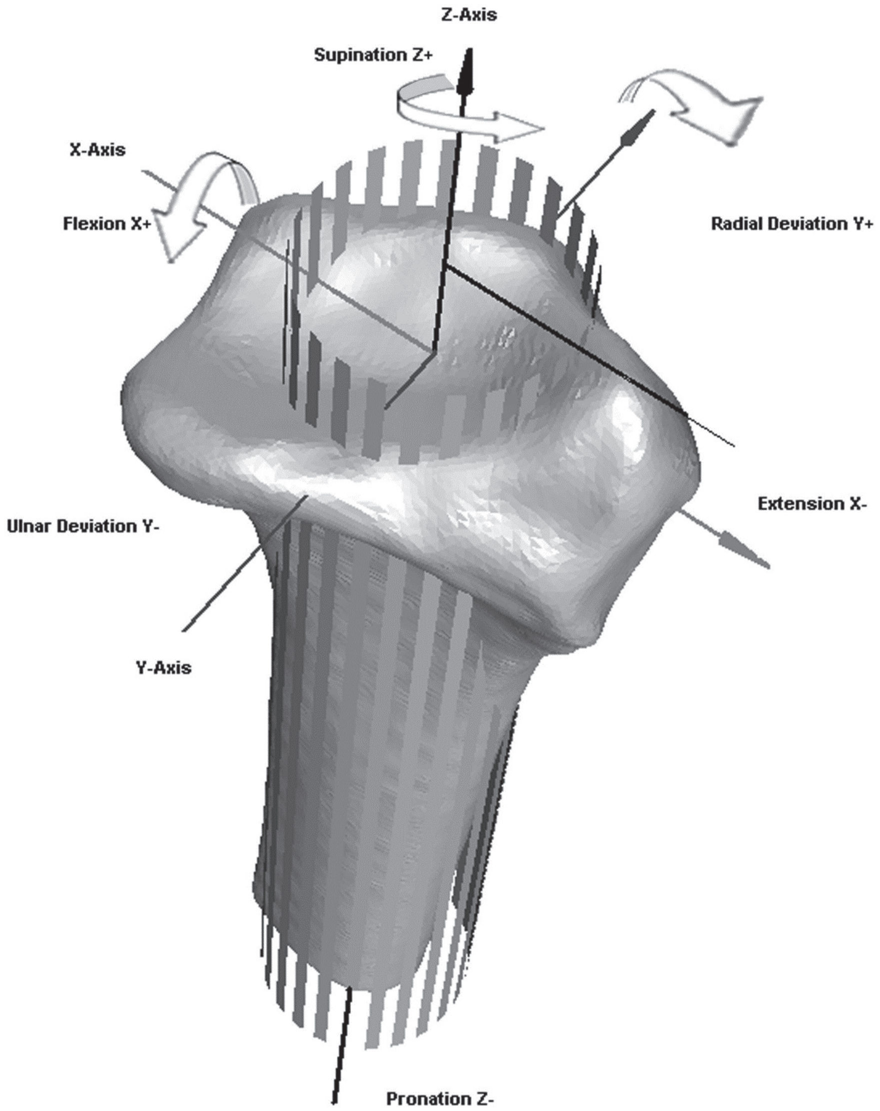


FIGURE 2. Anatomically based radial coordinate system (Foumani et al., 2009). Rotation around the X-axis indicates flexion (+) or extension (-). Rotation around the Y-axis indicates ulnar deviation (-) or radial deviation (+). Rotation around the Z-axis indicates supination (+) or pronation (-).

Reprinted from Journal of Biomechanics, 42, Foumani, M., Strackee, S.D., Jonges, R., Blankevoort, L., Zwinderman, A.H., Carelsen, B., Streekstra, G.J., In-vivo three-dimensional carpal bone kinematics during flexion-extension and radio-ulnar deviation of the wrist: Dynamic motion versus step-wise static wrist positions, 2664-2671, Copyright (2009), with permission from Elsevier.

The selection of the error covariance structure and the random effects structure was based on information criteria. To simplify the estimation of the model, only the observations were included per 5° of global wrist motion. The independent variables in the model were global wrist motion (coded as a categorical variable), gender and (non-dominant hand, as well as all possible two-way and three-way interaction terms of global wrist motion, gender and (non-)dominant hand. This model specification accounts for any type of effect modification between the independent variables. Due to the three-way interaction term gender*(non-)dominant hand*global wrist motion being significant, we chose to perform stratified analyses, using stratification by gender to evaluate the effect of hand dominance and stratification by hand dominance to evaluate the effect of gender. All models were stratified by rotational axis (flexion-extension, radial-ulnar deviation and pro-supination) and carpal bone (scaphoid, lunate and capitate). All statistical tests were two-sided and used a significance level of 5%.

RESULTS

Hand dominance and hypermobility assessment

All participants were Caucasian. Beighton score and ROM were almost identical for male and female participants and the active ROM did not seem to differ between dominant and non-dominant hand (Table 1). All the individual Beighton scores were <4, therefore no participants were excluded from the study.

Carpal kinematics

During flexion-extension of the wrist, the lunate and scaphoid flex when the wrist is flexed and extend when the wrist is extended, as shown in Figure 3. As Figure 3 also indicates, the lunate shows less flexion and extension compared to the scaphoid when the wrist is flexed or extended. Furthermore, the scaphoids' flexion-extension pattern is almost identical to that of the capitate.

Overall, carpal motion patterns during flexion-extension and radial-ulnar deviation of the wrist were not significantly different in male and female hands (Table 2, Supplementary Figure 5, 6, 8 and 9). However, radial-ulnar deviation of the lunate, scaphoid and capitate shows more variation between male and female participants when the wrist is maximally flexed and extended or maximally radial and ulnar deviated (Figure 3 and 4).

Differences are seen when comparing the dominant hand to the non-dominant hand. During flexion and extension of the wrist in males, the lunate, scaphoid and capitate of the non-dominant hand have a significantly larger radial-ulnar deviation range compared to the dominant hand (0.07°, 0.10°, 0.13° difference per degree of wrist motion respectively, all interaction effects $P<0.001$,) (Figure 3 and Table 3). During radial-ulnar deviation of the wrist in males, the dominant hand showed a significantly larger radial-ulnar deviation range (0.08° difference per degree of wrist motion, $P<0.001$) and pro-supination range (-0.04° difference per degree of wrist motion, $P=0.01$) of the lunate, and flexion-extension range (0.09° difference per degree of wrist motion, $P=0.045$) of the scaphoid compared to the non-dominant side (Table 3, Supplementary figure 7 and 10). No differences between the motion patterns of dominant and non-dominant hands in female participants were found, except for a little more pro-supination of the lunate of the dominant hand (-0.05° difference per degree of wrist motion, $P=0.002$) during radial-ulnar deviation of the wrist.

TABLE 1. Frequencies of hand dominance, mean and standard deviation (SD) of the Beighton score, and range of motion (ROM) of the wrist measured with the hand held goniometer in male and female volunteers.

	Male (n = 11)	Female (n=9)	Total (n=20)
Hand dominance			
Right	11	5	16
Left	0	4	4
Beighton	2 (1)	2 (2)	2 (1)
Active ROM dominant			
Flexion (deg.)	62 (14)	67 (7)	64 (11)
Extension (deg.)	81 (9)	77 (7)	79 (8)
Radial deviation (deg.)	28 (9)	32 (8)	30 (9)
Ulnar deviation (deg.)	30 (7)	35 (7)	32 (7)
Active ROM non-dominant			
Flexion (deg.)	65 (14)	66 (12)	65 (13)
Extension (deg.)	79 (10)	76 (7)	78 (9)
Radial deviation (deg.)	31 (11)	28 (6)	30 (9)
Ulnar deviation (deg.)	32 (10)	34 (3)	33 (7)

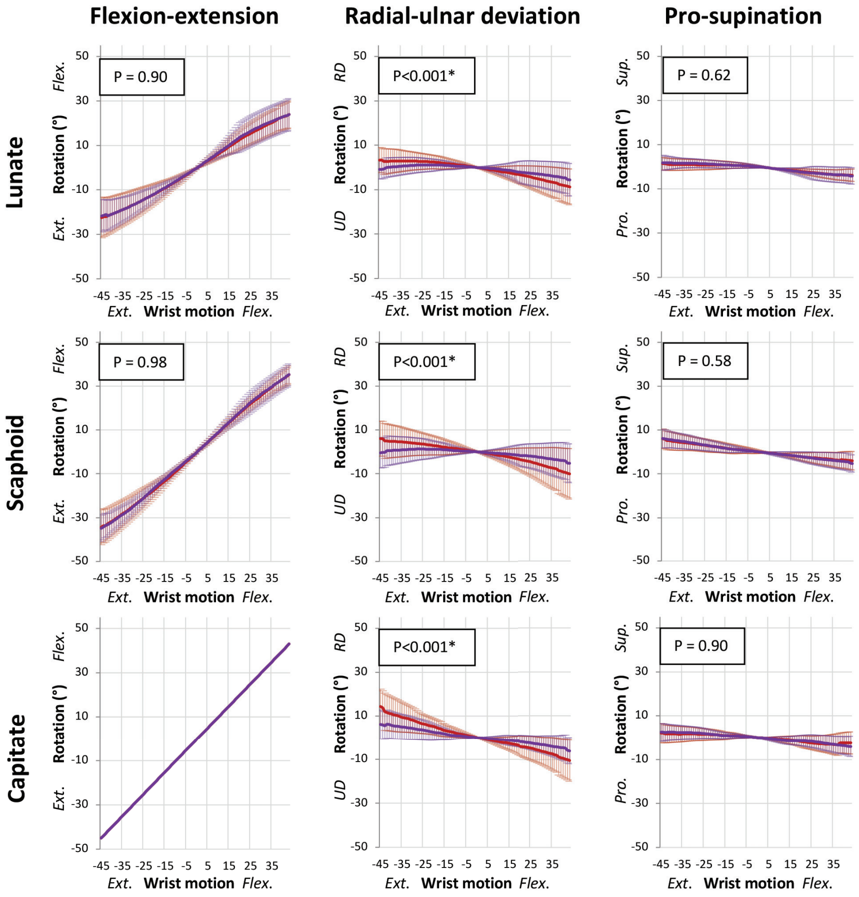


FIGURE 3. Comparison of dominant (purple) and non-dominant (red) motion patterns in male participants during flexion-extension of the wrist. Mean and standard deviations of flexion-extension, radial-ulnar deviation and pro-supination of the lunate, scaphoid and capitate are plotted for every degree of wrist motion. Flexion-extension motion of the capitate is presented as a straight purple line as the flexion-extension motion of the capitate was used to define the global wrist motion. The *P*-value for the difference due to dominance * wrist motion (trend) is presented.

Ext. extension, *Flex.* flexion, *Pro.* pronation, *Sup.* supination, *UD* ulnar deviation, *RD* radial deviation * $P < 0.05$

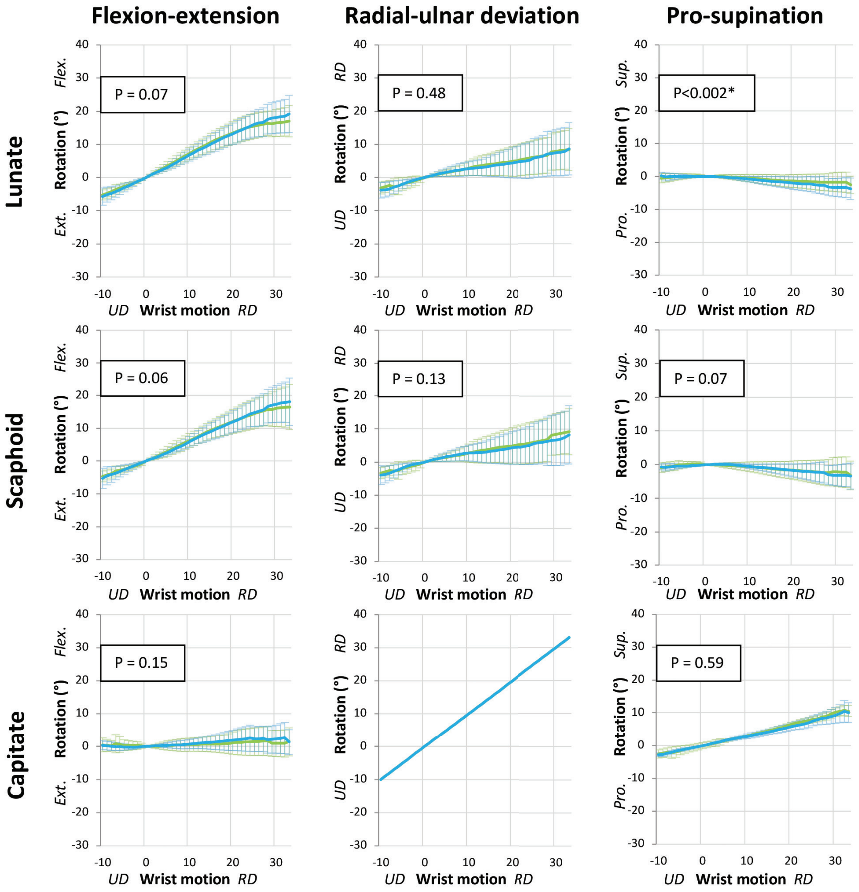


FIGURE 4. Comparison of dominant (blue) and non-dominant (green) motion patterns in female participants during radial-ulnar deviation of the wrist. Mean and standard deviations of flexion-extension, radial-ulnar deviation and pro-supination of the lunate, scaphoid and capitate are plotted for every degree of wrist motion. Radial-ulnar deviation of the capitate is presented as a straight blue line as the radial-ulnar deviation of the capitate was used to define the global wrist motion. The *P*-value for the difference due to dominance * wrist motion (trend) is presented.

Ext. extension, *Flex*. flexion, *Pro*. pronation, *Sup*. supination, *UD* ulnar deviation, *RD* radial deviation. * $P < 0.05$

TABLE 2. Estimated interaction effects of global wrist motion and gender in a linear mixed model.

		Flexion-extension wrist			*Radial-ulnar deviation wrist*		
		Difference (deg.)	**95% CI (deg.)**	***P*-value**	**Difference (deg.)**	**95% CI (deg.)**	***P*-value**
				Male versus female			
Dominant Hand							
Lunate	*FE*	0.04	-0.02 – 0.10	0.21	0.04	-0.09 – 0.16	0.55
	RU	0.08	-0.03 – 0.20	0.14	0.03	-0.14 – 0.20	0.69
	Pro-sup	0.01	-0.04 – 0.06	0.76	0.02	-0.07 – 0.12	0.61
Scaphoid	*FE*	0.01	-0.04 – 0.06	0.72	-0.02	-0.18 – 0.14	0.79
	RU	0.11	-0.06 – 0.28	0.18	0.07	-0.11 – 0.25	0.41
	Pro-sup	0.02	-0.06 – 0.09	0.68	0.04	-0.06 – 0.14	0.45
Capitate	*FE*	-	-	-	-0.08	-0.21 – 0.06	0.23
	RU	0.14	-0.04 – 0.33	0.12	-	-	-
	Pro-sup	0.02	-0.06 – 0.09	0.66	0.03	-0.06 – 0.12	0.47
Non-dominant Hand							
Lunate	*FE*	0.03	-0.05 – 0.11	0.41	0.02	-0.07 – 0.11	0.65
	RU	0.01	-0.14 – 0.16	0.88	-0.06	-0.22 – 0.11	0.46
	Pro-sup	0.02	-0.02 – 0.06	0.31	0.002	-0.08 – 0.09	0.96
Scaphoid	*FE*	0.01	-0.05 – 0.07	0.68	-0.05	-0.19 – 0.09	0.48
	RU	0.01	-0.21 – 0.24	0.91	0.003	-0.17 – 0.18	0.97
	Pro-sup	0.02	-0.05 – 0.09	0.53	0.02	-0.09 – 0.13	0.71
Capitate	*FE*	-	-	-	-0.05	-0.24 – 0.14	0.60
	RU	-0003	-0.22 – 0.22	0.98	-	-	-
	Pro-sup	0.05	-0.03 – 0.13	0.20	-0.01	-0.09 – 0.07	0.86

To compare the influence of gender, the interaction of gender and global wrist motion (gender * global wrist motion) was used as fixed effect in a linear mixed model. Flexion-extension of the capitate during flexion-extension motion of the wrist and radial-ulnar deviation of the capitate during radial-ulnar deviation of the wrist are presented as a "–", because the motion pattern of the capitate was used to define the global wrist motion. FE flexion-extension motion, RU radial-ulnar deviation motion, Pro-sup Pro-supination motion, CI confidence interval. * $P < 0.05$.

TABLE 3. Estimated interaction effects of global wrist motion and hand-dominance in a linear mixed model.

		Flexion-extension wrist			***Radial-ulnar deviation wrist***		
		Difference (deg.)	**95% CI (deg.)**	***P*-value**	**Difference (deg.)**	**95% CI (deg.)**	***P*-value**
		Dominant hand versus non-dominant hand					
<u>Male</u>							
Lunate	*FE*	0.02	-0.04 – 0.04	0.90	0.05	-0.02 – 0.13	0.17
	RU	0.07	0.05 – 0.09	< 0.001 *	0.08	0.04 – 0.12	< 0.001 *
	Pro-sup	-0.004	-0.02 – 0.01	0.62	-0.04	-0.07 – -0.01	0.01 *
Scaphoid	*FE*	-0.001	-0.03 – 0.03	0.97	0.09	0.002 – 0.17	0.045 *
	RU	0.10	0.08 – 0.13	< 0.001 *	0.05	-0.002 – 0.11	0.06
	Pro-sup	-0.004	-0.02 – 0.01	0.58	-0.03	-0.07 – 0.02	0.24
Capitate	*FE*	-	-	-	-0.01	-0.08 – 0.05	0.70
	RU	0.13	0.10 – 0.17	< 0.001 *	-	-	-
	Pro-sup	-0.01	-0.04 – 0.01	0.23	0.03	-0.01 – 0.07	0.19
<u>Female</u>							
Lunate	*FE*	0.003	-0.04 – 0.04	0.86	0.05	-0.004 – 0.11	0.07
	RU	0.01	-0.02 – 0.03	0.67	-0.02	-0.07 – 0.03	0.48
	Pro-sup	0.004	-0.01 – 0.02	0.60	-0.05	-0.08 to -0.02	0.002 *
Scaphoid	*FE*	0.01	-0.03 – 0.05	0.75	0.07	-0.002 – 0.16	0.06
	RU	0.01	-0.02 – 0.04	0.54	-0.04	-0.09 – 0.01	0.13
	Pro-sup	0.003	-0.01 – 0.02	0.72	-0.04	-0.08 – 0.003	0.07
Capitate	*FE*	-	-	-	0.05	-0.02 – 0.12	0.15
	RU	-0.01	-0.05 – 0.04	0.80	-	-	-
	Pro-sup	0.02	-0.002 – 0.05	0.07	-0.01	-0.03 – 0.02	0.59

To compare the influence of hand dominance, the interaction of hand dominance and global wrist motion (hand dominance * global wrist motion) was used as fixed effect in a linear mixed model. Flexion-extension of the capitate during flexion-extension motion of the wrist and radial-ulnar deviation of the capitate during radial-ulnar deviation of the wrist are presented as a "–", because the motion pattern of the capitate was used to define the global wrist motion. FE flexion-extension motion, RU radial-ulnar deviation motion, Pro-sup Pro-supination motion, CI confidence interval. * $P < 0.05$.

DISCUSSION

In the present study, in vivo carpal kinematics of the scaphoid, lunate and capitate in 20 healthy participants were assessed during flexion-extension and radial-ulnar deviation of the wrist with a dynamic 4D-CT imaging method. Other studies that used 4D-CT evaluated cadaveric wrists to describe radiocarpal kinematics and did not quantitatively analyze the motion patterns of individual carpal bones. We showed in a previous study that by quantitatively assessing in vivo carpal kinematics, small but significant differences can be found when axial load was applied to the wrist.[31] In hand surgery it is preferred to compare the injured side to the contralateral uninjured side or to reference data. In order to do this, it is crucial to know if there are no significant differences. We therefore studied the differences between gender and hand dominance using 4D-CT. No significant differences were found when comparing male and female carpal motion patterns. However, when comparing male motion patterns of the dominant hand with those of the non-dominant hands small but significant differences were found.

Gender

The effect of gender on ROM of the wrist is not widely studied. Klum et al.[23] assessed wrist function of uninjured wrists by studying wrist ROM measured with handheld goniometers. They found that females had greater wrist ROM compared to males. Wolfe et al.[29] found no difference between male and females when assessing 3D in vivo kinematics scaphocapitate, lunocapitate and scapholunate motion. De Roo et al [32] studied the motion of the scaphoid relative to the lunate using 4D-CT. They found that gender had a significant influence radial-ulnar deviation during flexion-extension of the wrist. They hypothesized that, since this was the only variable, which was significantly different, it may be due to the different sizes of the carpal bones. This was previously suggested to have an influence by Rainbow et al.[33] They, however, did not stratify for hand dominance. In our study we also found no differences when comparing carpal kinematics in male wrists with those of female wrists.

Hand dominance

In our study, significant differences were found within males when the dominant hand was compared to the non-dominant hand. The lunate of the dominant hand showed 0.08 degree more radial or ulnar deviation and 0.04 degree less pronation or supination per degree of wrist motion during radial-ulnar deviation of the wrist, and 0.07 degree less radial or ulnar deviation per degree of wrist motion during flexion-extension of the wrist. The scaphoid of the dominant hand had 0.09 degree more flexion or extension per degree of wrist motion during radial-ulnar deviation of the wrist and 0.10 degree less radial or ulnar deviation per degree of wrist motion during flexion extension of the wrist. The capitate of the dominant hand showed 0.13 degree less radial or ulnar deviation per degree of wrist motion during flexion-extension of the wrist. Previous studies assessed differences in ROM between dominant and non-dominant sides. Macedo and Magee [34] found a significant difference between dominant and non-dominant sides in 34 of the 60 ROM measured with a standard goniometer. However, these differences were minimal, and might therefore not be clinically relevant. A limitation of their study is that it does not tell us anything about the kinematics of individual carpal bones. Wolfe et al.[29] studied 3-dimensional in vivo kinematics of the lunate, scaphoid and capitate during four different flexion-extension positions of the wrist with a CT-scan and found no significant differences when comparing carpal motion patterns of the right and left wrist or between dominant and non-dominant hands. They, however, did not stratify for gender. These studies have methodological limitations, including using a standard goniometer or 3D analysis of the carpal bones in 4 different wrist positions, which may explain the difference in outcome. In 2019 de Roo et al [32] also used the 4D-CT to study the effect of hand dominance on the motion of the scaphoid relative to the lunate. They found no significant differences in the patterns during flexion-extension and radial-ulnar deviation of the wrist. Unfortunately, no stratification for gender was used.

This study has several limitations. First, this study is based on a small and relatively young group of participants with the same ethnicity, this limits extrapolation of our data. Second, the number of participants being studied is small. The group studied had a mean age of 28 years old and are from the same ethnicity (Caucasian). Older people and different ethnicities may show less or more carpal motion during wrist motion. Therefore, a larger, more variable group should be studied to fully evaluate normal wrist kinematics for different ages and ethnicities. Third, it was assumed that all examined wrists were uninjured based on self-reports of every volunteer. Fourth, our study did not evaluate the effect of carpal bone morphology on carpal kinematics. Baine et al [35] suggested that the morphology of the lunate may have a great influence on wrist kinematics. However, van de Giessen et al [36] found evidence that there are not just five bone shapes of the lunate but a whole scale of intermediate shapes. Because of the small group of participants and small differences that were found in this study, we decided not to investigate the influence of bone morphology on carpal kinematics. Fifth, 4D-CT approach is a relative complex method for studying carpal kinematics. Implementation of this technique in clinical practice will require training of medical staff on how to position and instruct the patient and how to analyze the data. Furthermore, the method will need further automation to make it more useful in clinical practice.

In conclusion, this study provides a better understanding of carpal kinematics by presenting normative data, providing motion patterns for every 5° of flexion-extension and radial ulnar deviation of the wrist and assessing the effect of gender and hand dominance on motion patterns of lunate, scaphoid and capitate. Dynamic volume scanning technologies are increasingly available, and methods and outcome of this study may be of great significance. Carpal pathologies are often difficult to diagnose because the pathomechanism is unknown. Dynamic assessment with the 4D-CT may be helpful to detect complex pathologies in an early stage. Our data may be used as a normative basis for studies focusing on pathological wrists such as in patients with scapholunate ligament injury. Although we found a difference when comparing carpal kinematics of the lunate, scaphoid and capitate of the dominant hand to the non-dominant hand, these differences were very small, and one could argue its importance in a clinical setting.

REFERENCES

1. Mat Jais, I.S. and S.C. Tay, Kinematic analysis of the scaphoid using gated four-dimensional CT. Clin Radiol, 2017. 72(9): p. 794 e1-794 e9.
2. Rainbow, M.J., et al., Functional kinematics of the wrist. J Hand Surg Eur Vol, 2016. 41(1): p. 7-21.
3. Schmitt, R., et al., Carpal instability. Eur Radiol, 2006. 16(10): p. 2161-78.
4. Kitay, A. and S.W. Wolfe, Scapholunate instability: current concepts in diagnosis and management. J Hand Surg Am, 2012. 37(10): p. 2175-96.
5. Pliefke, J., et al., Diagnostic accuracy of plain radiographs and cineradiography in diagnosing traumatic scapholunate dissociation. Skeletal Radiol, 2008. 37(2): p. 139-45.
6. Zanetti, M., J. Bram, and J. Hodler, Triangular fibrocartilage and intercarpal ligaments of the wrist: does MR arthrography improve standard MRI? J Magn Reson Imaging, 1997. 7(3): p. 590-4.
7. Morley, J., J. Bidwell, and M. Bransby-Zachary, A comparison of the findings of wrist arthroscopy and magnetic resonance imaging in the investigation of wrist pain. J Hand Surg Br, 2001. 26(6): p. 544-6.
8. Patel, R.M., et al., Comparisons of three radiographic views in assessing for scapholunate instability. Hand (N Y), 2015. 10(2): p. 233-8.
9. Sulkers, G.S., et al., The diagnostic accuracy of wrist cineradiography in diagnosing scapholunate dissociation. J Hand Surg Eur Vol, 2014. 39(3): p. 263-71.
10. Bryce, T.H., Certain Points in the Anatomy and Mechanism of the Wrist-Joint Reviewed in the Light of a Series of Rontgen Ray Photographs of the Living Hand. J Anat Physiol, 1896. 31(Pt 1): p. 59-79.
11. McMurtry, R.Y., et al., Kinematics of the wrist. II. Clinical applications. J Bone Joint Surg Am, 1978. 60(7): p. 955-61.
12. Arkless, R., Cineradiography in normal and abnormal wrists. Am J Roentgenol Radium Ther Nucl Med, 1966. 96(4): p. 837-44.
13. Crisco, J.J., R.D. McGovern, and S.W. Wolfe, Noninvasive technique for measuring in vivo three-dimensional carpal bone kinematics. J Orthop Res, 1999. 17(1): p. 96-100.
14. Feipel, V., et al., Bi- and three-dimensional CT study of carpal bone motion occurring in lateral deviation. Surg Radiol Anat, 1992. 14(4): p. 341-8.
15. Kobayashi, M., et al., Normal kinematics of carpal bones: a three-dimensional analysis of carpal bone motion relative to the radius. J Biomech, 1997. 30(8): p. 787-93.
16. Snel, J.G., et al., Quantitative in vivo analysis of the kinematics of carpal bones from three-dimensional CT images using a deformable surface model and a three-dimensional matching technique. Med Phys, 2000. 27(9): p. 2037-47.
17. Moritomo, H., et al., The scaphotrapezio-trapezoidal joint. Part 2: A kinematic study. J Hand Surg Am, 2000. 25(5): p. 911-20.
18. Choi, Y.S., et al., Four-dimensional real-time cine images of wrist joint kinematics using dual source CT with minimal time increment scanning. Yonsei Med J, 2013. 54(4): p. 1026-32.

19. Edirisinghe, Y., et al., Dynamic motion analysis of dart throwers motion visualized through computerized tomography and calculation of the axis of rotation. J Hand Surg Eur Vol, 2014. 39(4): p. 364-72.

20. Zhao, K., et al., A technique for quantifying wrist motion using four-dimensional computed tomography: approach and validation. J Biomech Eng, 2015. 137(7).

21. Foumani, M., et al., In-vivo three-dimensional carpal bone kinematics during flexion-extension and radio-ulnar deviation of the wrist: Dynamic motion versus step-wise static wrist positions. J Biomech, 2009. 42(16): p. 2664-71.

22. Brinkhorst, M., et al., Quantifying in vivo scaphoid, lunate, and capitate kinematics using four-dimensional computed tomography. Skeletal Radiol, 2020.

23. Klum, M., et al., Normative data on wrist function. J Hand Surg Am, 2012. 37(10): p. 2050-60.

24. Garcia-Elias, M., et al., Influence of joint laxity on scaphoid kinematics. J Hand Surg Br, 1995. 20(3): p. 379-82.

25. Beighton, P., L. Solomon, and C.L. Soskolne, Articular mobility in an African population. Ann Rheum Dis, 1973. 32(5): p. 413-8.

26. Carelsen, B., et al., Detection of in vivo dynamic 3-D motion patterns in the wrist joint. IEEE Trans Biomed Eng, 2009. 56(4): p. 1236-44.

27. Neu, C.P., J.J. Crisco, and S.W. Wolfe, In vivo kinematic behavior of the radio-capitate joint during wrist flexion-extension and radio-ulnar deviation. J Biomech, 2001. 34(11): p. 1429-38.

28. Kaufmann, R., et al., Kinematics of the midcarpal and radiocarpal joints in radioulnar deviation: an in vitro study. J Hand Surg Am, 2005. 30(5): p. 937-42.

29. Wolfe, S.W., C. Neu, and J.J. Crisco, In vivo scaphoid, lunate, and capitate kinematics in flexion and in extension. J Hand Surg Am, 2000. 25(5): p. 860-9.

30. Dobbe, J.G.G., et al., Evaluation of a Quantitative Method for Carpal Motion Analysis Using Clinical 3-D and 4-D CT Protocols. IEEE Trans Med Imaging, 2019. 38(4): p. 1048-1057.

31. Brinkhorst, M., et al., Effects of axial load on in vivo scaphoid and lunate kinematics using four-dimensional computed tomography. J Hand Surg Eur Vol, 2020. 45(9): p. 974-980.

32. de Roo, M.G.A., et al., A four-dimensional-CT study of in vivo scapholunate rotation axes: possible implications for scapholunate ligament reconstruction. J Hand Surg Eur Vol, 2019. 44(5): p. 479-487.

33. Rainbow, M.J., et al., Gender differences in capitate kinematics are eliminated after accounting for variation in carpal size. J Biomech Eng, 2008. 130(4): p. 041003.

34. Macedo, L.G. and D.J. Magee, Differences in range of motion between dominant and nondominant sides of upper and lower extremities. J Manipulative Physiol Ther, 2008. 31(8): p. 577-82.

35. Bain, G.I., et al., The effect of lunate morphology on the 3-dimensional kinematics of the carpus. J Hand Surg Am, 2015. 40(1): p. 81-9 e1.

36. van de Giessen, M., et al., Statistical descriptions of scaphoid and lunate bone shapes. J Biomech, 2010. 43(8): p. 1463-9.

APPENDICES

Supplementary FIGURE 5

Supplementary FIGURE 6

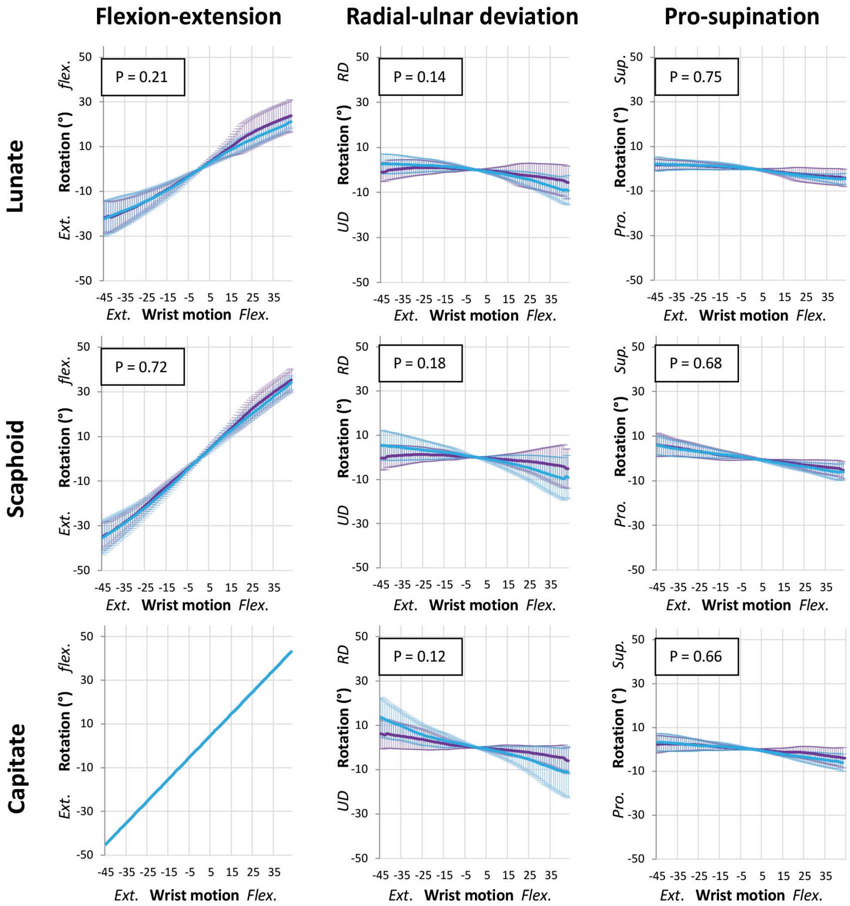
Supplementary FIGURE 7

Supplementary FIGURE 8

Supplementary FIGURE 9

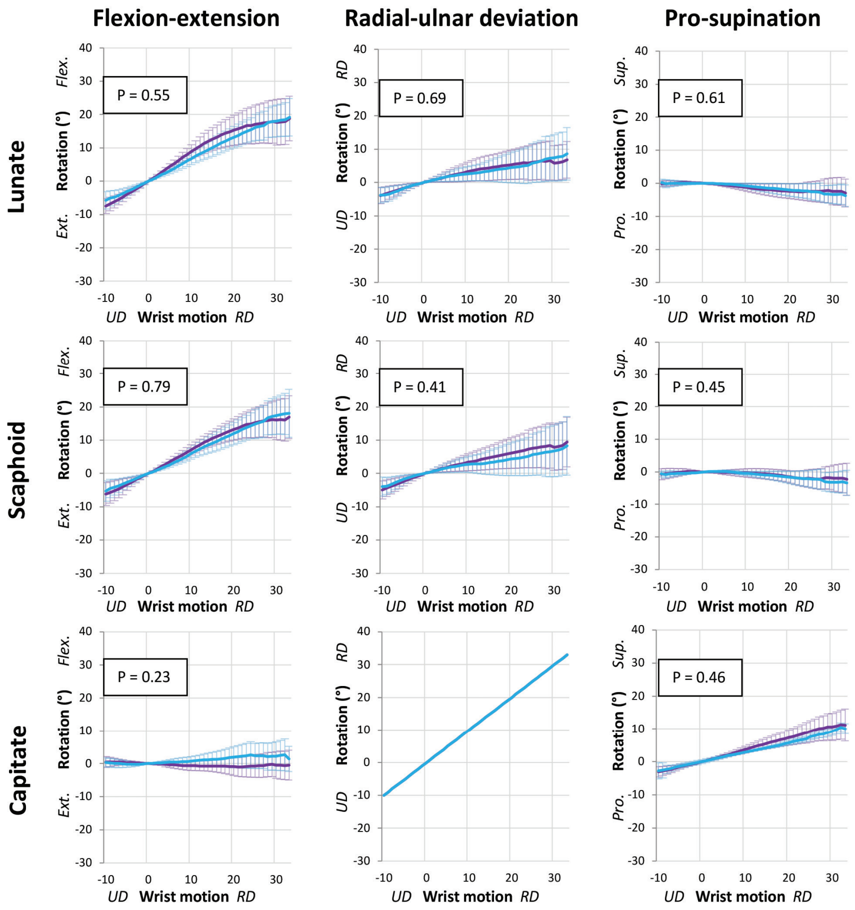
Supplementary FIGURE 10

Supplementary FIGURE 5



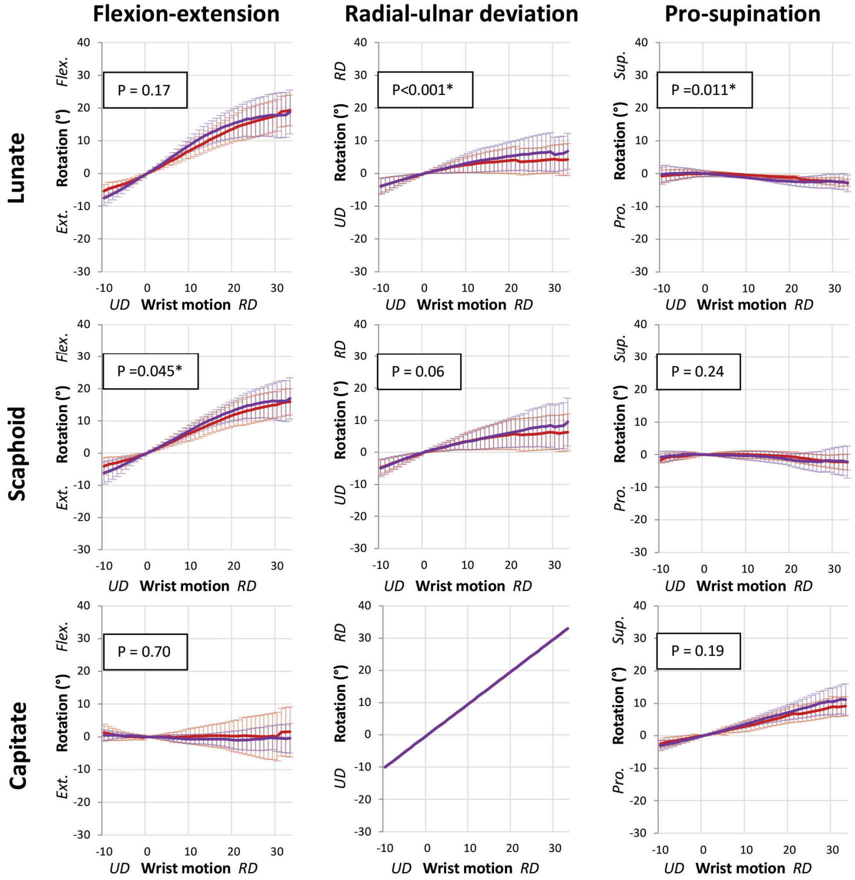
Comparison of female (blue) and male (purple) motion patterns in dominant hand during flexion-extension of the wrist. Mean and standard deviations of flexion-extension, radial-ulnar deviation and pro-supination of the lunate, scaphoid and capitate are plotted for every degree of wrist motion. Flexion-extension motion of the capitate is presented as a straight blue line as the flexion-extension motion of the capitate was used to define the global wrist motion. The *P*-value for the difference due to dominance * wrist motion (trend) is presented.
Ext. extension, *Flex.* flexion, *Pro.* pronation, *Sup.* supination, *UD* ulnar deviation, *RD* radial deviation * $P < 0.05$

Supplementary FIGURE 6



Comparison of female (blue) and male (purple) motion patterns in dominant hand during radial-ulnar deviation of the wrist. Mean and standard deviations of flexion-extension, radial-ulnar deviation and pro-supination of the lunate, scaphoid and capitate are plotted for every degree of wrist motion. Radial-ulnar deviation motion of the capitate is presented as a straight blue line as the radial-ulnar deviation motion of the capitate was used to define the global wrist motion. The *P*-value for the difference due to dominance * wrist motion (trend) is presented. *Ext.* extension, *Flex.* flexion, *Pro.* pronation, *Sup.* supination, *UD* ulnar deviation, *RD* radial deviation * $P < 0.05$

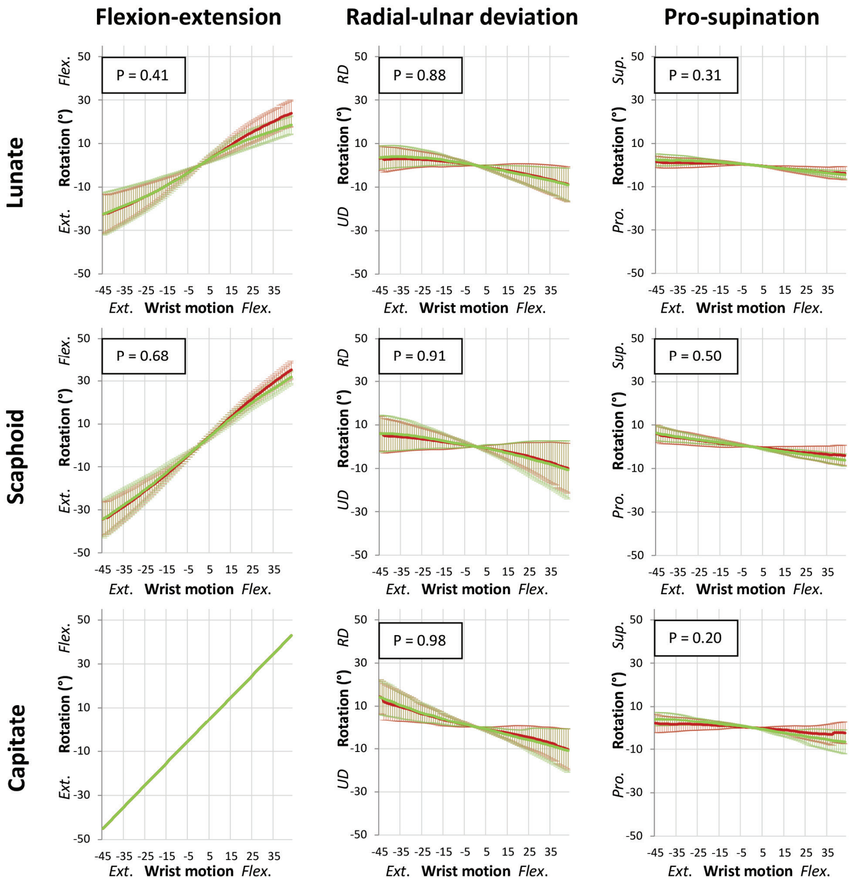
Supplementary FIGURE 7



Comparison of dominant (purple) and non-dominant (red) motion patterns in male participants during radial-ulnar deviation of the wrist. Mean and standard deviations of flexion-extension, radial-ulnar deviation and pro-supination of the lunate, scaphoid and capitate are plotted for every degree of wrist motion. Radial-ulnar deviation of the wrist of the capitate is presented as a straight purple line as the radial-ulnar deviation motion of the capitate was used to define the global wrist motion. The *P*-value for the difference due to dominance * wrist motion (trend) is presented.

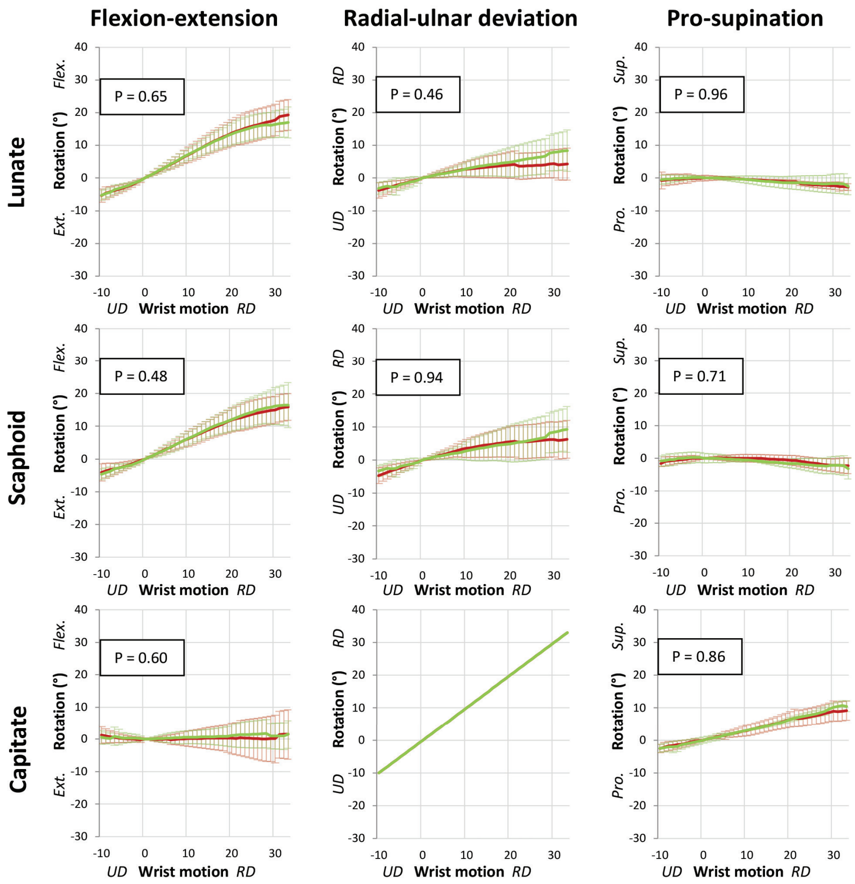
Ext. extension, *Flex*. flexion, *Pro*. pronation, *Sup*. supination, *UD* ulnar deviation, *RD* radial deviation * $P < 0.05$

Supplementary FIGURE 8



Comparison of female (green) and male (red) motion patterns in non-dominant hand during flexion-extension of the wrist. Mean and standard deviations of flexion-extension, radial-ulnar deviation and pro-supination of the lunate, scaphoid and capitate are plotted for every degree of wrist motion. Flexion-extension motion of the capitate is presented as a straight green line as the flexion-extension motion of the capitate was used to define the global wrist motion. The *P*-value for the difference due to dominance * wrist motion (trend) is presented. *Ext*. extension, *Flex*. flexion, *Pro*. pronation, *Sup*. supination, *UD* ulnar deviation, *RD* radial deviation * $P < 0.05$

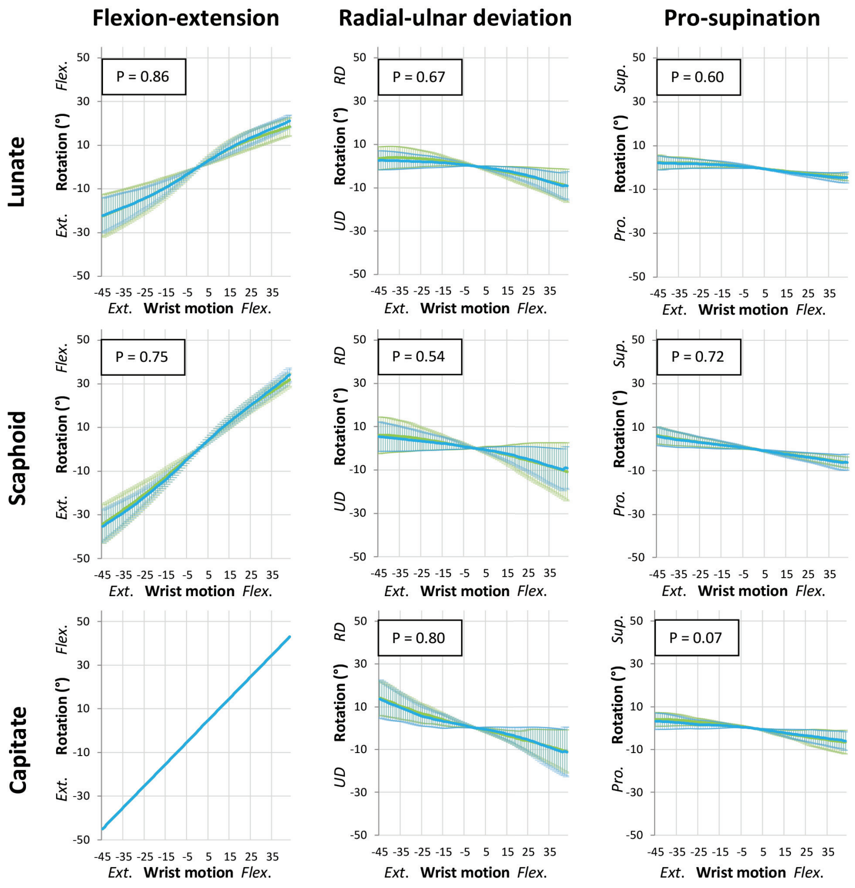
Supplementary FIGURE 9



Comparison of female (green) and male (red) motion patterns in non-dominant hand during radial-ulnar deviation of the wrist. Mean and standard deviations of flexion-extension, radial-ulnar deviation and pro-supination of the lunate, scaphoid and capitate are plotted for every degree of wrist motion. Radial-ulnar deviation of the wrist of the capitate is presented as a straight green line as the radial-ulnar deviation motion of the capitate was used to define the global wrist motion. The *P*-value for the difference due to dominance * wrist motion (trend) is presented.

Ext. extension, *Flex*. flexion, *Pro*. pronation, *Sup*. supination, *UD* ulnar deviation, *RD* radial deviation * $P < 0.05$

Supplementary FIGURE 10



Comparison of dominant (blue) and non-dominant (green) motion patterns in female participants during flexion-extension of the wrist. Mean and standard deviations of flexion-extension, radial-ulnar deviation and pro-supination of the lunate, scaphoid and capitate are plotted for every degree of wrist motion. Flexion-extension motion of the capitate is presented as a straight blue line as the flexion-extension motion of the capitate was used to define the global wrist motion. The *P*-value for the difference due to dominance * wrist motion (trend) is presented.

Ext. extension, *Flex.* flexion, *Pro.* pronation, *Sup.* supination, *UD* ulnar deviation, *RD* radial deviation * $P < 0.05$.

6

CHAPTER 7

Effects of axial load on in vivo scaphoid and lunate kinematics using four-dimensional computed tomography

M.E. Brinkhorst, G.J. Streekstra, J.M. van Rosmalen, S.D. Strackee, S.E.R. Hovius

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ABSTRACT

Purpose: To study the effect of axial load on lunate and scaphoid kinematics during flexion-extension and radial-ulnar deviation of the uninjured wrist using four-dimensional computed tomography

Methods: A prospective study, both wrists of 20 uninjured Caucasian volunteers were assessed using 4D-CT during active flexion-extension and radial-ulnar deviation. Each scan was performed twice (one without and one with load (100N performed by the participant by clenching their fist). A linear mixed model was used to compare the carpal motion patterns.

Results: When applying axial load to the wrist results in a more flexed, radially deviated and pronated position of the lunate and scaphoid during flexion-extension of the wrist compared to when no load is applied. A larger pronation and supination range of the lunate and scaphoid was seen when the wrist was flexed and extended under axial load, whereas a larger flexion and extension range of the lunate and scaphoid occurred during radial-ulnar deviation of the wrist when axial load was applied.

Conclusions: This data provides a better understanding of in vivo carpal kinematics in uninjured wrists. When under axial load, the position and kinematics of the scaphoid and lunate change significantly.

INTRODUCTION

The lunate and scaphoid form a complex joint which has been studied extensively. Together with the triquetrum, they form an intercalated segment between the distal carpal row and the bones of the forearm. The alignment of the bones is maintained through the shape of the bones, surrounding joint surfaces, ligaments, and the axial load crossing the joint from the metacarpals to the forearm muscles. In 1997, Kobayahi et al.[1] described that when axial load is applied the wrist maintained its stability and flexion, radial deviation and supination of the proximal row is facilitated as a result of a complex mechanism which involved interaction between intercarpal and midcarpal joint geometries and different ligament constrains.

Instability of the scapholunate joint is most commonly caused by injury to the scapholunate interosseous ligament.[2] If left untreated this injury will lead to advanced secondary osteoarthritis such as scapholunate advanced collapse (SLAC).[3] Early diagnosis is therefore crucial to enable early treatment which may prevent persistent and mostly progressive instability resulting into degenerative osteoarthritis. In this context, it is important to understand carpal kinematics in the uninjured wrist before interpreting the carpal kinematics of the injured wrist and making subsequent treatment decisions.

Diagnostic techniques have evolved over the past decades. Specific radiographs, such as the clenched fist view, cineradiography, computerized tomography (CT) and magnetic resonance imaging (MRI) provided an initial understanding of wrist kinematics. More recently, dynamic four- dimensional CT studies (4D CT) have been introduced.[4-8] Current studies using 4D CT have focused on the gap size between the scaphoid and lunate when axial load is applied or on carpal kinematics during the dart-throwing motion.[9-12] The application of tendon loading during cadaveric experiments to simulate natural stabilizing joint compression has shown changes in the orientation of the carpal bones and carpal kinematics.[1, 13, 14] The effect of axial load on scaphoid and lunate kinematics during active flexion-extension and radial-ulnar deviation are yet unknown, but it is thought to be of great importance in diagnosing and treating carpal and ligamentous injury. The aim of this in vivo study was to investigate the effect of axial load on lunate and scaphoid kinematics during flexion-extension and radial-ulnar deviation of the uninjured wrist using 4D CT.

METHODS

Ethical approval was obtained before the study from our institution. Written informed consent was obtained from all participants. Both wrists of 20 uninjured participants (11 men and nine women) with a mean age of 27 years (SD 4, range 19) were studied. All participants stated they had not had any wrist surgery, significant trauma to their wrists or any symptoms of carpal instability. The Beighton score was used to assess hypermobility with a score of 4 being the clinical level for hypermobility.[15] All participants were Caucasian and their individual Beighton scores were al less than 4, so no participants were excluded and all 40 wrists were used in the analysis.

Participants were put in a prone position with one arm 180° abducted; the forearm was placed in custom-made motion guiding device [6] with the elbow extended and the forearm in pronation fixed to a framework to guide the hand and wrist during the 4D CT recordings. Metacarpals were placed in a natural position on a handle that was attached to the framework. The handle was designed to measure grip strength which could be assessed by the participant and the study investigator during CT recordings. Load on the metacarpals is directed along the longitudinal axis of the bone. By clenching the wrist the force applied on the metacarpals compressed the wrist. Participants were instructed to lightly grab the handlebar when no axial load was applied, or to clench their fist to produce 100 N (approximately 10 kgf). Each participant received individualized information and training before scanning to ensure they understood the flexion-extension and radial-ulnar deviation motion of the wrist and the speed needed to complete each motion cycle.

A Brilliance 64-slice CT scanner (Philips Medical System, Best, The Netherlands) was used. A static CT image (120 kV, 75 mAs) of the wrist in neutral was taken to reconstruct the bony geometry of the scaphoid, lunate, capitate and distal portion of the radius (length scanned was 4 cm). The neutral position of the wrist was defined as the dorsal part of the middle metacarpal being aligned with the dorsal part of the radius. Subsequently, one flexion-extension followed by a radial-ulnar deviation motion movement was imaged with a 4D CT protocol (120 kV, 15 mAs, 64 x 0.625 mm). Participants started each motion cycle with a relaxed grip around the handlebar. After completion of one motion cycle, a pause of 4 minutes was taken and subsequently the same motion cycle was repeated with a clenched fist. A total of four scans per wrist were obtained. Each scan was made as a smooth motion within 10 seconds.

After completion of all four dynamic scans of both wrists the scaphoid, lunate, capitate and distal portion of the radius were segmented in the static scan using a region-growing algorithm described by Carelsen and Foumani.[16] All scans of the left wrist were mirrored to present as a right wrist to assist data analysis. Using custom made software, an estimation of the rotational parameters of each individual bone relative to the neutral position was obtained by registering the segmented bones from the neutral scan to the corresponding bones of each timeframe of the 4D CT scan. Carpal bone kinematical parameters, during wrist motion were calculated for each time frame of the 4D CT.[17] Motion patterns of the scaphoid, lunate and capitate were described using an anatomically-based radial coordinate system, described by Kobayashi.[18] Essentially, the axes of the scaphoid, lunate and capitate were defined as being parallel to this anatomical coordinate system of the radius with the wrist in a neutral position. Global wrist motion was described as the rotation in degrees of the capitate relative to the radius.[19, 20] Carpal motion was quantified as rotation in degrees of the scaphoid, lunate and capitate relative to the radius. Flexion (X+), extension (X-), radial deviation (Y+), ulnar deviation (Y-), supination (Z+) and pronation (Z-) were defined as the rotation in degrees around the axes of the anatomical coordinate system of the radius.[6, 16, 18]

Linear mixed models were used to compare the carpal motion patterns with and without axial load.[21] The different values of global wrist motion were considered as repeated measurements. To account for correlations between observations within a motion cycle, observations of different levels global wrist motion were assumed to be correlated according to a first-order autoregressive moving average (ARMA(1,1)) covariance structure. The effect of this covariance structure is that higher correlations are assumed between similar levels of global wrist motion than between global wrist motions that are far apart. To further account for the within-subject correlations, random intercepts and random slopes of global wrist motion were included in the model, so that the level of the carpal motion pattern and its linear association with global wrist motion were assumed to vary among the participants. The selection of the error covariance structure and the random effects structure was based on information criteria that take into account the goodness of fit and the complexity of different possible model specifications. To simplify the estimation of the model, only the observations were included per 5° of global wrist motion. Independent variables in the model were global wrist motion, axial load, and the interaction effect of load and global wrist motion. All models were stratified by rotational axis (flexion-extension, radial-ulnar deviation and pronation-supination) and carpal bone (scaphoid or lunate). All statistical tests were two-sided and a significance level of 5 % was set.

RESULTS

Carpal kinematics during flexion-extension of the wrist (Table 1; Figure 1)

During flexion and extension of the wrist the lunate and scaphoid closely follow the motion of the capitate. Without axial loading, the lunate showed less flexion-extension than the scaphoid (46° vs 75°). When axial load was applied the scaphoid and lunate had a significantly more flexed position (approximately 4° for both) compared to no axial loading . This more flexed position during axial load had no influence on flexion-extension range of the lunate or scaphoid (respectively 44° and 75°).

In the loaded and unloaded situations, the lunate and scaphoid showed similar radial-ulnar deviation motion patterns during flexion-extension of the wrist. When the wrist was extended they deviated radially and when the wrist was flexed they deviated ulnarly. Without axial loading, the lunate and scaphoid showed similar ranges of radial-ulnar deviation (respectively 11° and 13°) during flexion-extension of the wrist. When axial loading was applied, the lunate had a small but significantly more radially deviated position. This more radially deviated position under axial load had no influence on the radial-ulnar deviation range (10°) of the lunate.

The pronation-supination pattern of the lunate and scaphoid during flexion-extension of the wrist was similar and small. When the wrist was extended they supinated and when the wrist was flexed they pronate. Without axial loading, the range of motion was relatively small (respectively, 7° and 13°). When axial loading was applied the lunate and scaphoid showed a small but significantly more pronated position than when no load was applied. Also a significantly smaller range of pronation and supination of the lunate and scaphoid was seen (respectively 4° and 12°).

Carpal kinematics during radial-ulnar deviation of the wrist (Table 1; Figure 2)

During radial-ulnar deviation of the wrist the lunate and scaphoid showed similar motion patterns. When the wrist was ulnarly deviated the lunate and scaphoid extended and when the wrist was radially deviated they flexed. Without axial loading, the lunate showed slightly more flexion-extension than the scaphoid (respectively 29° vs 24°). When axial load was applied the lunate and scaphoid did not show any change in their position with no axial loading . Although no change in position was found, the lunate and scaphoid showed a significantly larger flexion-extension range (respectively 32° and 26°) than the range without loading. The lunate and scaphoid showed similar radial-ulnar deviation motion patterns with and without axial load during radial-ulnar deviation of the wrist. No changes in radial-ulnar deviation range or position were observed when axial loading was compared to no axial loading. With and without axial loading, almost no pronation-supination of the lunate and scaphoid during radial-ulnar deviation of the wrist was seen (1° for both).

TABLE 1. Estimated effects of global wrist motion and load in a linear mixed model

		Flexion-extension wrist		*Radial-ulnar deviation wrist*	
		Difference (95% CI) (°)	p-value	Difference (95% CI) (°)	p-value
		Estimated effect of axial load			
Lunate	FE	-3.9 (-5.7 to -2.1)	**<0.001**	-0.6 (-2.0 to 0.8)	0.38
	RU	-1.6 (-3.1 to -0.1)	**0.035**	-0.8 (-1.7 to 0.1)	0.10
	Pro-sup	0.7 (0.1 to 1.4)	**0.033**	0.6 (0.0 to 1.2)	0.05
Scaphoid	FE	-3.8 (-5.4 to -2.2)	**<0.001**	-1.1 (-3.0 to 0.8)	0.27
	RU	-1.4 (-3.7 to -0.9)	0.23	-0.7 (-1,6 to 0.2)	0.12
	Pro-sup	1.2 (0.4 to 2.1)	**0.003**	0.7 (-0.0 to 1.5)	0.06
Capitate	FE	-	-	0.5 (-1.20 to 2.3)	0.54
	RU	-4.4 (-6.9 to -1.9)	**<0.001**	-	-
	Pro-sup	0.0 (-1.3 to 1.3)	0.98	1.7 (0.9 to 2.5)	**<0.001**
		Estimated interaction effect of axial load and wrist motion			
Lunate	FE	-0.004 (-0.03 to -0.02)	0.73	-0.08 (-0.11 to -0.04)	**<0.001**
	RU	0.005 (-0.01 to -0.02)	0.43	0.02 (-0.007 to -0.04)	0.19
	Pro-sup	-0.02 (-0.03 to -0.01)	**<0.001**	-0.01 (-0.03 to 0.002)	0.08
Scaphoid	FE	-0.008 (-0.03 to 0.01)	0.42	-0.06 (-0.10 to -0.02)	**0.007**
	RU	0.009 (-0.01 to -0.02)	0.24	-0,02 (-0.04 to 0.008)	0.18
	Pro-sup	-0.01 (-0.02 to -0.003)	**0.006**	-0.02 (-0.04 to -0.003)	**0.02**
Capitate	FE	-	-	-0.02 (-0.05 to 0.02)	0.40
	RU	-0.02 (-0.04 to -0.002)	**0.03**	-	-
	Pro-sup	-0.016 (-0.03 to -0.002)	**0.02**	-0.04 (-0.06 to -0.02)	**<0.001**

To evaluate the combined effect of axial load (yes/no) and wrist motion (in degrees), the main effects and the interaction effect of these variables were used as fixed effects in a linear mixed model. The main effect of load describes the effect of load on rotation/position of the carpal bone at a global wrist motion of 0°; the interaction effect describes the increase in the effect of load on rotation per degree increase in wrist motion which describes the motion pattern of the carpal bone. FE: flexion-extension motion; RU: radial-ulnar deviation motion; Pro-sup: pronation-supination motion; CI: confidence interval. Statistically significant values are shown in bold font.

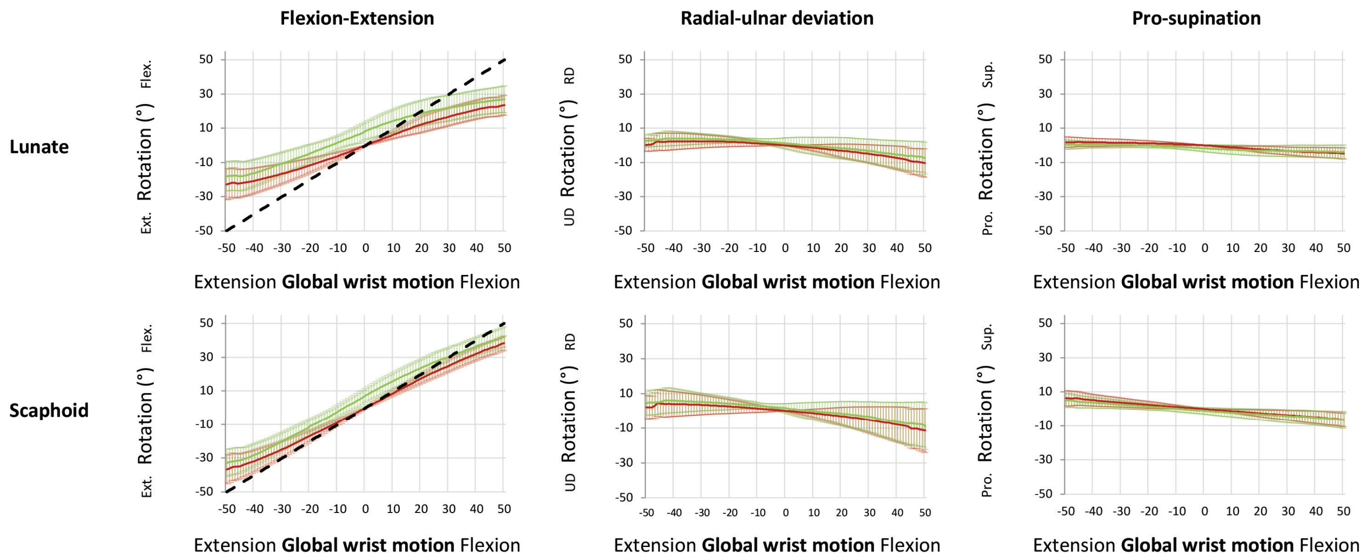

FIGURE 1. Comparison of loaded (green) and non-loaded (red) motion patterns in healthy volunteers during flexion-extension of the wrist. Mean and standard deviations of flexion-extension, radial-ulnar deviation and pro-supination of the lunate and scaphoid are plotted for every degree of wrist motion. Flexion-extension motion of the capitate is presented as a straight dotted line as the flexion-extension motion of the capitate was used to define the global wrist motion.
Ext.:extension; Flex.: flexion; UD: ulnar deviation; RD: radial deviation; Pro.: pronation; Sup.: supination.

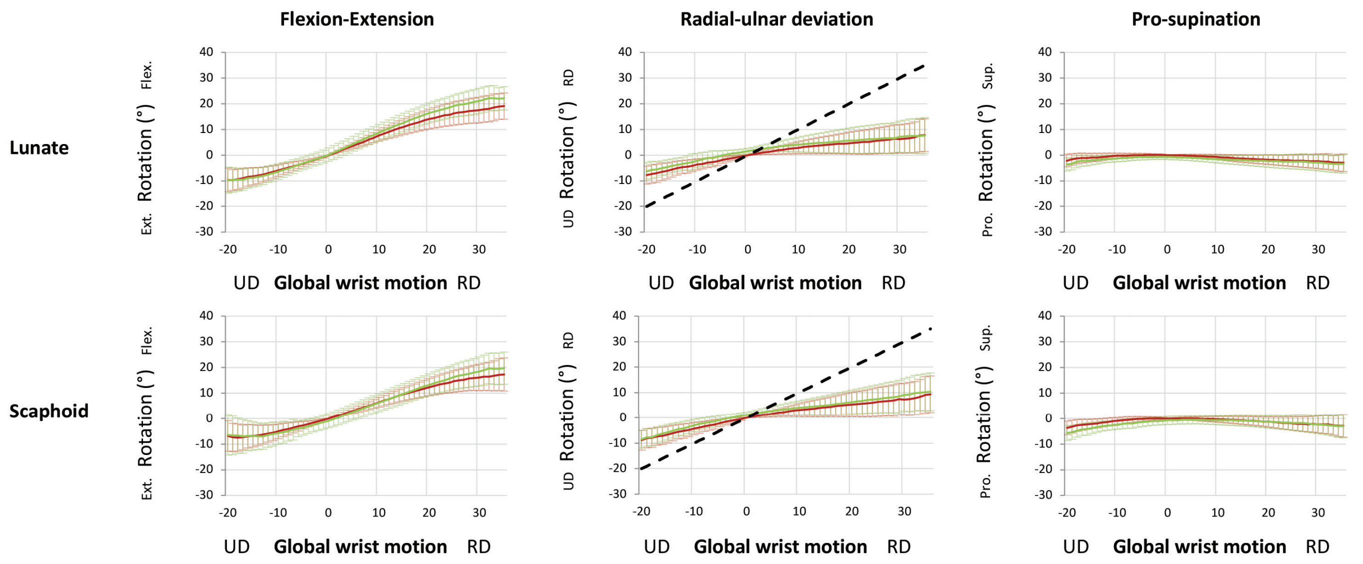

FIGURE 2. Comparison of loaded (green) and non-loaded (red) motion patterns in healthy volunteers during radial-ulnar deviation of the wrist. Mean and standard deviations of flexion-extension, radial-ulnar deviation and pro-supination of the lunate and scaphoid are plotted for every degree of wrist motion. Flexion-extension motion of the capitate is presented as a straight dotted line as the radial-ulnar deviation motion of the capitate was used to define the global wrist motion.
Ext.:extension; Flex.: flexion; UD: ulnar deviation; RD: radial deviation; Pro.: pronation; Sup.: supination.

7

DISCUSSION

The aim of this in vivo study was to assess the effect of axial load on lunate and scaphoid kinematics during flexion-extension and radial-ulnar deviation in the uninjured wrist using 4D CT. We found that the application of axial load to the wrist results in a more flexed, radially deviated and pronated position of the lunate and scaphoid during flexion-extension of the wrist compared to when there is no load. This phenomenon was not seen when axial load was applied during radial-ulnar deviation of the wrist. A larger pronation and supination range of the lunate and scaphoid during axial load was seen when the wrist was flexed and extended. A larger flexion and extension range of the lunate and scaphoid was seen during radial-ulnar deviation of the wrist when axial load was applied.

The diagnosis of scapholunate injuries can be difficult. Injuries of the scapholunate ligament can vary in severity from partial disruption to a complete tear. Several diagnostic options are available, all with their own flaws. Plain radiographs and MRI scans lack specificity as they are static examinations which cannot detect alterations in carpal motion.[22] Stress radiography, like the clenched pencil view, have low sensitivity and specificity regarding ligament injurie.[23] Dynamic imaging techniques, such as cineradiography, have high sensitivity and specificity but may miss subtle bony changes and diagnosis can be investigator dependent as there is a steep learning curve.[24, 25] Wrist arthroscopy remains the reference standard owing to its ability to assess the kinematic behaviour of the carpal bones. However it is an invasive method with some risks for example nerve injury, infection and stiffness. Furthermore, traction on the wrist is not physiological neither is the insertion of a 2.7mm wide instrument. The introduction of 4D CT could provide a non-invasive alternative to assess carpal kinematics and may help to diagnose acute stage scapholunate ligament injuries, without the disadvantages of other methods.

Axial load has been used to identify dynamic instability patterns by precipitating subtle carpal mal-alignment through clenched fist radiographs.[26, 27] It is, however, highly dependent of the position of the wrist during compression. Few dynamic studies of the wrist have been done with the joint loaded.[14, 26, 28, 29] An altered motion pattern during axial load compression may be an indicator of scapholunate ligament injury. However, an understanding of normal imaging anatomy is necessary before defining pathology.

Kobayashi et al.[1] studied the changes in carpal bone alignment in 13 cadaver specimens secondary to axial load. A load of 89 N was applied through the wrist motor tendons followed by biplanar radiographic analysis of the carpal bones with the wrist in a neutral position. They concluded that with axial loading the scaphoid and lunate rotated into a more flexed, radially deviated and supinated position. Owing to the oblique alignment of the scaphoid in the sagittal and coronal planes, axial load will result in a flexed and radially deviated position of the scaphoid. The present study found similar results when axial load was applied during flexion-extension of the wrist. However, these changes were not seen when the wrist was radial-ulnar deviated. These differences may be because load in the wrist is not evenly distributed and may be localized to specific areas during specific wrist movements.[30]

Gupta.[13] studied the effect of physiological axial loading on carpal alignment in lateral radiographs of 20 uninjured wrists before and after general anaesthesia with muscle relaxants. It was found that physiological axial load, applied by the forearm muscles, tends to flex the lunate and scaphoid. It was suggested that the scaphoid is subject to more force than other bones of the proximal carpal row. Force through the trapezium and trapezoid and the anteriorly placed distal pole of the scaphoid, cause it to be pushed into a flexed position when axial load is applied. The lunate is subsequently forced into flexion because of the attachment of the scapholunate ligament. In the present study we also found a more flexed position of the lunate and scaphoid when axial loading was applied during flexion-extension of the wrist.

Foumani et al.[14] studied the effect of tendon loading on in-vitro carpal kinematics using a four-dimensional rotational X-ray imaging system. Carpal kinematics were compared with and without applying 50 N load to the extensor tendons and 50 N load to the flexor tendons while the wrist was passively moved into flexion-extension or radial-ulnar deviation. In contrast to the results in our study and previous studies investigating the effects of load on carpal kinematics [13, 18], they found that during flexion-extension of the wrist the scaphoid and lunate were less flexed when load was applied. They also observed that during radial-ulnar deviation of the wrist, the lunate and scaphoid were more radially deviated and showed more supination. The data in our study did not support this. This may be a result of different experimental conditions; their study was a cadaver study and the wrist was moved passively by a motion device.

There are several limitations to our study. The sample was relatively small. However it is currently the largest group of in vivo uninjured wrists that has been studied with the dynamic 4D CT method. I It was assumed after the selection process that all wrists were uninjured and “normal”. Nevertheless this does not rule out wrist disorders or congenitally different shapes of the carpal bones affecting the findings. Implementation of this technique in clinical practice will require training of medical staff on how to position and instruct the patient and how to analyse the data. Radiation exposure should always be kept to a minimum.

However, the maximum effective dose in our study was approximately 0.15 mSv for each participant. This is, according to the International Commission on radiological protection (ICRP), classified as having minor risk.[31]

The data in this study provide a better understanding of in vivo carpal kinematics in uninjured wrists and shows the effect of axial loading on the lunate and scaphoid kinematics. They may serve as normative data for future studies focusing on carpal kinematics after ligament repair, scaphoid fractures or in the diagnosis of ligamentous injury.

REFERENCES

1. Kobayashi, M., et al., Axial loading induces rotation of the proximal carpal row bones around unique screw-displacement axes. J Biomech, 1997. 30(11-12): p. 1165-7.

2. Kitay, A. and S.W. Wolfe, Scapholunate instability: current concepts in diagnosis and management. J Hand Surg Am, 2012. 37(10): p. 2175-96.

3. O'Meeghan, C.J., et al., The natural history of an untreated isolated scapholunate interosseus ligament injury. J Hand Surg Br, 2003. 28(4): p. 307-10.

4. Athlani, L., et al., Assessment of scapholunate instability with dynamic computed tomography. J Hand Surg Eur, 2020. 45(4): p. 375-382.

5. Carr, R., et al., Four-Dimensional Computed Tomography Scanning for Dynamic Wrist Disorders: Prospective Analysis and Recommendations for Clinical Utility. J Wrist Surg, 2019. 8(2): p. 161-167.

6. de Roo, M.G.A., et al., A four-dimensional-CT study of in vivo scapholunate rotation axes: Possible implications for scapholunate ligament reconstruction. J Hand Surg Eur, 2019. 44(5): p. 479-487.

7. Rauch, A., et al., Four-dimensional CT Analysis of Wrist Kinematics during Radioulnar Deviation. Radiology, 2018. 289(3): p. 750-758.

8. White, J., G. Couzens, and C. Jeffery, The use of 4D-CT in assessing wrist kinematics and pathology: a narrative view. Bone Joint J, 2019. 101-B(11): p. 1325-1330.

9. Demehri, S., et al., Scapholunate kinematics of asymptomatic wrists in comparison with symptomatic contralateral wrists using four-dimensional CT examinations: initial clinical experience. Skeletal Radiol, 2016. 45(4): p. 437-46.

10. Edirisinghe, Y., et al., Dynamic motion analysis of dart throwers motion visualized through computerized tomography and calculation of the axis of rotation. J Hand Surg Eur Vol, 2014. 39(4): p. 364-72.

11. Garcia-Elias, M., X. Alomar Serrallach, and J. Monill Serra, Dart-throwing motion in patients with scapholunate instability: a dynamic four-dimensional computed tomography study. J Hand Surg Eur, 2014. 39(4): p. 346-52.

12. Kelly, P.M., et al., Dynamic CT Scan of the Normal Scapholunate Joint in a Clenched Fist and Radial and Ulnar Deviation. Hand (N Y), 2017: p. 1558944717726372.

13. Gupta, A., Change of carpal alignment under anaesthesia: role of physiological axial loading on carpus. Clin Biomech (Bristol, Avon), 2002. 17(9-10): p. 660-5.

14. Foumani, M., et al., The effect of tendon loading on in-vitro carpal kinematics of the wrist joint. J Biomech, 2010. 43(9): p. 1799-805.

15. Beighton, P., L. Solomon, and C.L. Soskolne, Articular mobility in an African population. Ann Rheum Dis, 1973. 32(5): p. 413-8.

16. Foumani, M., et al., In-vivo three-dimensional carpal bone kinematics during flexion-extension and radio-ulnar deviation of the wrist: Dynamic motion versus step-wise static wrist positions. J Biomech, 2009. 42(16): p. 2664-71.

17. Woltring, H.J., 3-D attitude representation of human joints: a standardization proposal. J Biomech, 1994. 27(12): p. 1399-414.

18. Kobayashi, M., et al., Normal kinematics of carpal bones: a three-dimensional analysis of carpal bone motion relative to the radius. J Biomech, 1997a. 30(8): p. 787-93.

19. de Lange, A., J.M. Kauer, and R. Huiskes, Kinematic behavior of the human wrist joint: a roentgen-stereophotogrammetric analysis. J Orthop Res, 1985. 3(1): p. 56-64.

20. Neu, C.P., J.J. Crisco, and S.W. Wolfe, In vivo kinematic behavior of the radio-capitate joint during wrist flexion-extension and radio-ulnar deviation. J Biomech, 2001. 34(11): p. 1429-38.

21. Verbeke, G. and G. Molenberghs, Linear Mixed Models for Longitudinal Data. 2001: Springer New York.

22. Bateni, C.P., et al., Imaging key wrist ligaments: what the surgeon needs the radiologist to know. AJR Am J Roentgenol, 2013. 200(5): p. 1089-95.

23. Kuo, C.E. and S.W. Wolfe, Scapholunate instability: current concepts in diagnosis and management. J Hand Surg Am, 2008. 33(6): p. 998-1013.

24. Pliefke, J., et al., Diagnostic accuracy of plain radiographs and cineradiography in diagnosing traumatic scapholunate dissociation. Skeletal Radiol, 2008. 37(2): p. 139-45.

25. Sulkers, G.S.I., et al., Wrist cineradiography: a protocol for diagnosing carpal instability. J Hand Surg Eur Vol, 2018. 43(2): p. 174-178.

26. Truong, N.P., et al., Wrist instability series: increased yield with clinical-radiologic screening criteria. Radiology, 1994. 192(2): p. 481-4.

27. Lee, S.K., et al., Comparison of radiographic stress views for scapholunate dynamic instability in a cadaver model. J Hand Surg Am, 2011. 36(7): p. 1149-57.

28. Meade, T.D., L.H. Schneider, and K. Cherry, Radiographic analysis of selective ligament sectioning at the carpal scaphoid: a cadaver study. J Hand Surg Am, 1990. 15(6): p. 855-62.

29. Wolfe, S.W., A. Gupta, and J.J. Crisco, 3rd, Kinematics of the scaphoid shift test. J Hand Surg Am, 1997. 22(5): p. 801-6.

30. Short, W.H., et al., Analysis of the kinematics of the scaphoid and lunate in the intact wrist joint. Hand Clin, 1997. 13(1): p. 93-108.

31. ICoRP, I., Radiological Protection in Biomedical Research. A report of Committee 3 adopted by the International Commission on Radiological Protection. Ann ICRP, 1991. 22(3): p. 1-28, v-xxiv.

CHAPTER 8

Discussion and future perspectives

Treatment of the osteoarthritic wrist remains a clinical challenge. Pain and stiffness are the most common symptoms of wrist osteoarthritis. They form a large burden for patients and simple activities in daily living can become increasingly difficult. Total wrist arthrodesis has been shown to relieve pain, however, it also has a large negative impact on long-term function of the upper extremity and quality of life.[1] Twenty of the 22 patients with a wrist arthrodesis would even have preferred a motion-preserving technique.[1] Therefore, the main goal of treatment is relieving pain while preserving wrist motion.

PART 1 – Results after motion-preserving surgery in SNAC or SLAC wrists

The aim of part 1 of this thesis was to understand the effect and burden patients encounter after motion-preserving surgery. In stage 2 SNAC or SLAC wrist, the go-to motion-preserving surgical treatment remains either proximal row carpectomy (PRC) or intercarpal fusion like four corner fusion (FCF). Since the description of Stamm in 1944 [2], proximal row carpectomy serves as a predictable and simple technique with quick recovery for stage 2 SNAC and SLAC patients. In 1986 Watson and Ryu [3] first reported about four-corner fusion and over the past years it has proven to predictably relieve pain while preserving the native radiolunate joint and therefore preserving some wrist motion.

Despite the several motion-preserving techniques that have been described and outcomes studied, controversy still exists on which treatment and technique of stage 2 SNAC or SLAC wrist is superior. The indication for FCF or PRC remain unchanged, and both are good options for stage 2 SNAC or SLAC wrists. Both procedures have their pros and cons which results in a lack of consensus among surgeons on which procedure to use for this stage.

In **Chapter 2**, a dynamic assessment of grip strength and range of motion was used to study the results after PRC and FCF for stage 2 SNAC or SLAC wrists. We found that peak grip strengths and grip sustainability after PRC were higher than after FCF. It was presumed that in FCF, the wrists are more restricted when ulnar deviated and extended, causing lesser efficiency for the muscle tendon units and therefore less strength. Furthermore, PRC wrists showed a larger flexion-extension arc and a circumduction curve concentric with non-injured wrists. We concluded that after an FCF, the wrist lacks motion in the dart-throwing functional plane. This is probably due to fusion of the midcarpal joint which allows this type of motion. Based on these findings we conclude that PRC wrists have better functional outcome than FCF wrists.

In recent literature we found two systematic reviews which compared clinical outcomes after PRC to outcomes after FCF.[4, 5] Mulford et al. concluded that grip strength, pain relief and subjective outcomes were comparable for both surgical groups.[4] However, range of motion was slightly less after FCF and more complications (nonunion, dorsal impingement and hardware problems) were seen in FCF patients. The risk of osteoarthritic change after PRC appeared to be higher but was overall asymptomatic. Saltzman et al., included only articles that assessed both PRC and FCF patients. They found more post-operative wrist extension, flexion, and a larger flexion-extension motion arc after PRC, but a larger radial deviation after FCF. In contrast with Mulford et al., they found that after FCF, post-operative grip strength as a percentage of the contralateral side was greater. However, proportional change compared to pre-operative was not significantly different compared to PRC. DASH scores were not significantly different between both groups, but in the FCF group there were significantly more complications. Selection bias may have been inherent for both studies when comparing both procedures as patients with midcarpal osteoarthritis cannot undergo a PRC due to midcarpal osteoarthritis and therefore pre-operative wrist motion is supposed to be better compared to the FCF group. Overall, previous studies demonstrated little differences between PRC and FCF compared which is comparable to our findings.

The question remained, however, whether these differences affected patients during activities of daily living. Therefore, our next step was to study the effect of PRC and FCF on patient's ability to perform activities of daily living. To assess the influence of PRC or FCF on the activities of daily living, in **Chapter 3**, we compared the time taken to perform tasks using the timed Sollerman test and its related handgrips. After a PRC, patients performed most activities more quickly compared to FCF patients. An exception was found for tasks that required larger torque strength such as opening a jar, which was performed more quickly by FCF patients. PRC patients also reported higher satisfaction and less disability after surgery compared to FCF patients. Therefore, we concluded that overall better functional outcome and satisfaction was found after the PRC procedure.

Our findings indicate that stage 2 SNAC or SLAC patients have better functional outcomes after PRC compared to patients after an FCF. However, there are some limitations in both studies. The number of patients is small in both groups and follow-up time of the PRC group is shorter compared to the FCF group. However, previous studies have indicated that outcomes in patients over 35 years after FCF [6] and PRC [7] do not worsen up to 10 years after surgery.

Although differences are in favor of PRC for stage 2 SNAC or SLAC wrists, it is contraindicated for stage 3 due to degeneration of the capitate head. For wrists with stage 3 SNAC or SLAC, intercarpal fusion such as four-corner fusion (LCTH) or lunocapitate (LC) arthrodesis remain the best motion-preserving option.[6, 8] Another method is to use a partial capitate prosthesis as a cap when the proximal pole of the capitate has evidence of osteoarthritis.[9, 10] Long-term follow-up will have to prove the outcome of this salvage procedure. For stage 4 (end stage) arthritis of the wrist, total wrist arthroplasty is an attractive option for motion preservation. It enables patients to perform activities of daily living easier by preserving some wrist motion, but they also have shown a high incidence of implant failure, reactive synovitis and osteolysis.[11, 12] Since the first total wrist arthroplasty implant was developed, newer generation implants were designed by learning from previous mistakes. A perfect implant duplicates the complexity of multiple articulations across the wrist joint while improving stability and strength. Several studies have already reported good results after modern “fourth generation” total wrist implants in rheumatoid arthritis patients, but they have not been reported for post-traumatic wrist osteoarthritis patients.[13, 14]

In **Chapter 4,** we studied the early functional results following total wrist arthroplasty with the Universal 2 total wrist system in patients with stage 4 SNAC or SLAC. The Universal 2 total wrist implant is a fourth-generation implant which has been widely used as a motion-preserving technique for patients with extensive carpal osteoarthritis. We found that all range of motion directions and grip strength, 6 and 12 months after surgery, did not change compared to pre-operative values. Furthermore, DASH scores improved (from 53 preoperatively to 14 at 12 months follow-up) which indicates that the Universal 2 total wrist prosthesis should be considered in patients with end-stage noninflammatory wrist osteoarthritis.

Previous literature on the Universal 2 prosthesis showed conflicting and incomplete data and was mostly based on patients with rheumatoid arthritis.[13-15] Recently, Zijlker et al.[16] published their long-term results (mean follow-up 11 years) of the Universal 2 total wrist arthroplasty. Eight of the 26 wrists studied had a history of post-traumatic wrist osteoarthritis and the others mostly due to rheumatoid arthritis. They found no significant difference in implant failure when comparing inflammatory patients to noninflammatory patients. Overall, patients reported being satisfied with the results after the implant was placed and only 5 were converted to total wrist arthrodesis. Berber et al.[17] performed a systematic review of total wrist arthroplasty and arthrodesis in wrist arthritis. Only 6% of all patients who received a total wrist implant had a history of post-traumatic wrist osteoarthritis.

Srnec et al. compared all generations of total wrist implants and concluded that the newest (fourth) generation total wrist implants (Biaxial, Universal 2 and Re-motion) provide a significant improvement in function and lower complication rates compared to earlier generations of implants.[18] Cooney et al. retrospectively compared the Biaxial, Universal 2 and Re-motion total wrist implants and concluded that the implants provide good pain relief and functional motions in over 80% of all cases.[19] Recently the Freedom wrist implant was introduced, which is a modification of the Universal 2 wrist implant. The Freedom is supposed to have a more physiological motion and improved stability in association with an ellipsoidal articulation. Unfortunately, the outcomes of the Freedom implant have not been studied yet.

Literature describing results of total wrist arthroplasty in patients with post-traumatic wrist osteoarthritis is scarce. However, the results that are published presenting results of the newest wrist implants are starting to show more promising results compared to the earlier used wrist implants. Unfortunately, results like total knee or hip implants are still far away. We believe that the high patient satisfaction after total wrist implants should be valued with the only alternative treatment option for stage 4 wrist osteoarthritis being total wrist arthrodesis.

Future Perspectives

Overall, level 1 comparative studies with long-term follow-up is needed, for example:

- A randomized controlled trial between intercarpal fusion and proximal row carpectomy for stage 2 SNAC or SLAC wrists with comparison of the long-term results.
- Set-up an international database for all implanted wrist implants which can support future research on end stage noninflammatory wrist osteoarthritis.

PART 2 – In vivo carpal kinematics

The aim of part 2 of this thesis was to improve the understanding of in vivo carpal kinematics to enable earlier diagnosis of complex wrist injuries and may improve or change their treatment. Analyzing carpal kinematics is likely to result in technical challenges. Analysis with conventional methods, such as plain radiographs and videofluoroscopy, is almost impossible due to the small size of carpal bones and many articulations. Historically, carpal kinematics were studied using invasive markers or cadaver models. Unfortunately, each of these methods suffer from limitations that hamper clinical use such as being invasive, unable to measure kinematics of each separate carpal bone or lacking normal muscle tone.

We chose to use one of the newest methods to analyse in vivo kinematics of individual bones: the four-dimensional CT (4D-CT). It is based on a non-invasive method without markers. With 4D-CT, it is possible to quantitatively analyze in vivo carpal kinematics during active wrist motion. It has the potential to provide earlier diagnosis of carpal pathologies and assess carpal kinematics postoperatively. In literature there are several 4D-CT-based methods suggested to analyze carpal kinematics or to assess instability. Some assessed scapholunate instability by subjective observations [20] or quantitatively measured the gap between the scaphoid and the lunate.[21, 22] Others used double-oblique multiplanar reformation (MPR) to assess pisotriquetral motion [23] or total hysteresis to assess the integrity of the carpal ligaments and potential measure of stability.[24]

Several limitations of the 4D-CT were found when reviewing literature. Overall, sample sizes were small (usually 4 or less cases) which results in a lack of data with normal ranges. Secondary, to measure the scapholunate distance 2D analyses are used in slices of a CT-scan. This may result in missing abrupt changes and not using the true motion of the wrist. Furthermore, when the 4D-CT is used to diagnose scapholunate ligament rupture by reviewing the scapholunate distance on 2D images, wide ranges were found in uninjured wrists (0.67mm to 1.19mm) versus distance in suspected ruptures (1.5mm to 6mm).[25] Therefore, we believe that normative data of true 3D in vivo carpal kinematics is necessary to understand in vivo carpal kinematics in uninjured wrists which could also be used as a reference when injured wrists are studied.

In **Chapter 5**, we assessed the test-retest reliability of the 4D-CT to study translation and rotation of the lunate and scaphoid. This method was first introduced by Carelsen et al.[26] We studied both wrists of 20 healthy volunteers during flexion-extension and radial-ulnar deviation motion using the 4D-CT. We found the method to be reliable with coefficient of multiple correlation (CMC) values tending towards 1 (0.84 – 1) and root mean square deviations (RMSD) between 1.17° and 4.29°. Future research must show if the low RMSD value can discriminate between uninjured wrists and wrists with a scapholunate ligament rupture.

From previous studies we already learned that the scaphoid and lunate follow the capitate during flexion-extension and radial-ulnar deviation of the wrist. The scaphoid follows the capitate more closely than the lunate. The kinematics of the lunate and scaphoid found in our study agreed with previously published data.[27, 28] Furthermore, the lunate and scaphoid extend when the wrist is ulnarly deviated and flex when the wrist is radially deviated, showing a coupled motion between scaphoid and lunate which is consistent with previous reports.[27-30]

In patients, the Range of Motion of the injured wrist is usually compared to the uninjured contralateral wrist or to normative data to diagnose injuries. Multiple studies were previously conducted to investigate normal carpal kinematics. Klum et al.[31] found that gender and dominance influence the range of motion of the wrist when studied with handheld goniometers. This suggests that it may also have an influence on carpal kinematics.

In **Chapter 6** we therefore evaluated the effect of gender and hand dominance on in vivo kinematics of the scaphoid, lunate and capitate in uninjured wrists using 4D-CT analysis. We found no significant difference when comparing male to female carpal motion patterns. However, when studying the effect hand dominance, we found a significant difference within males when the dominant hand was compared to the non-dominant hand. More ulnar deviation and more radial deviation was seen in the lunate, scaphoid, and capitate of the non-dominant hand when the wrist was flexed and subsequently extended. Although these differences were significant, they are small and might therefore not be clinically relevant, this may be demonstrated when analyzing patients with proven SL-ligament injuries using the 4D-CT.

Previous studies on the effect of gender and hand dominance on carpal kinematics are limited. Wolfe et al.[32] studied in vivo carpal kinematics during flexion and extension of the wrist using a 3D-CT registration algorithm without markers. They found, in agreement with us, no significant differences when comparing carpal kinematics of males to females or dominant to non-dominant hands. Unfortunately, they did not stratify for gender and did not assess carpal kinematics during radial-ulnar deviation.

In 2010, Foumani et al.[33] showed that applying tendon loading during cadaveric experiments resulted in changes in orientation of the carpal bones and carpal kinematics. They concluded that the rotations changed in the same plane as global wrist motion, depending on articular surface geometry, and mechanical properties of the ligaments, which was also proposed by Kobayashi et al. and Gupta et al.[34, 35]

Therefore, in **Chapter 7**, we studied the effect of axial load on lunate and scaphoid kinematics during flexion-extension and radial-ulnar deviation in uninjured wrists using 4D-CT. We found that applying axial load to the wrist results in a more flexed, radially deviated, and pronated position of the lunate and scaphoid during flexion-extension of the wrist compared to when no load is applied. A larger pronation and supination range of the lunate and scaphoid was seen when the wrist was flexed and extended under axial load, whereas a larger flexion and extension range of the lunate and scaphoid occurred during radial-ulnar deviation of the wrist when axial load was applied. In future research on the reliability of the 4D-CT scan in patients with SL-ligament injury, these findings may be used as a normative basis.

Our findings did not support the data presented by Foumani et al.[33] They described in vitro carpal kinematics with and without applying axial load through 50N load to the extensor tendons and 50N load to the flexor tendons while the wrist was passively moved (flexion-extension or radial-ulnar deviation). In contrast to our findings, they found that during flexion-extension of the wrist the scaphoid and lunate were less flexed when load was applied. They also observed that during radial-ulnar deviation of the wrist, the lunate and scaphoid were more radially deviated and showed more supination. These differences may be the result of differences in experimental conditions (e.g., cadaver study, passive wrist motion, or different load distribution).

In this thesis we did not differentiate between the two lunate morphologies. Type 1 lunates do not articulate with the hamate while type 2 lunates do articulate with the hamate. The presence of a type 2 lunate, which is the presence of a medial facet, is reported in 27%-73%.[36-39] It has been suggested that type 2 lunates develop arthritic changes at the proximal hamate pole due to changes in carpal kinematics.[39, 40] Abe et al.[41] evaluated the carpal kinematics of lunate, hamate, capitate, and triquetrum in relationship to the two types of lunate using 3D-CT. They found significant differences in carpal kinematics of the triquetrum relative to the lunate during radial-ulnar deviation. They concluded that a type 2 lunate may increase the chance of lunotriquetral ligament tears and may cause proximal hamate osteoarthritis. Unfortunately, they did not study the effect on the kinematics of the scaphoid. In 2018 Quan Pang et al.[37] studied the relationship between type 1 and type 2 lunates in the development of the dorsal intercalated segmental instability (DISI) in patients with SL ligament injuries. They found no differences in the development of DISI or scapholunate instability between the two types of lunate.

Future Perspectives

4D-CT imaging provides us with a better understanding of true carpal kinematics. The effect of intercarpal ligament injury on the carpal kinematics may objectively be analysed with the 4D-CT. Hypothetically, the 4D-CT scan may serve as a method to early diagnose and treat ligament injuries of the wrist. To prove the diagnostic value of the 4D-CT imaging techniques and eventually implement it into the clinical workflow, we believe the following steps need to be taken in the future:

- Set up a larger carpal kinematic 4D-CT study focusing on different age groups and the influence of lunate morphology. With this data an “uninjured” wrist model can be built to which the injured wrist can be compared to.
- Diagnostic study for diagnosing SL ligament ruptures using 4D-CT and compare it to standard CT or videofluoroscopy.
- Set up a prospective study focusing on the changes of carpal kinematics using 4D-CT after SL ligament injury and after SL ligament repair, to improve the knowledge on the effect of surgical procedures on carpal kinematics.
- Study on the clinical value of dynamic distance maps for OA detection.

REFERENCES

1. Adey, L., D. Ring, and J.B. Jupiter, Health status after total wrist arthrodesis for post-traumatic arthritis. J Hand Surg Am, 2005. 30(5): p. 932-6.

2. Stamm, T.T., Excision of the Proximal Row of the Carpus. Proc R Soc Med, 1944. 38(2): p. 74-5.

3. Watson, H.K. and J. Ryu, Evolution of arthritis of the wrist. Clin Orthop Relat Res, 1986(202): p. 57-67.

4. Mulford, J.S., et al., Proximal row carpectomy vs four corner fusion for scapholunate (Slac) or scaphoid nonunion advanced collapse (Snac) wrists: a systematic review of outcomes. J Hand Surg Eur Vol, 2009. 34(2): p. 256-63.

5. Saltzman, B.M., et al., Clinical outcomes of proximal row carpectomy versus four-corner arthrodesis for post-traumatic wrist arthropathy: a systematic review. J Hand Surg Eur Vol, 2015. 40(5): p. 450-7.

6. Bain, G.I. and A.C. Watts, The outcome of scaphoid excision and four-corner arthrodesis for advanced carpal collapse at a minimum of ten years. J Hand Surg Am, 2010. 35(5): p. 719-25.

7. DiDonna, M.L., T.R. Kiefhaber, and P.J. Stern, Proximal row carpectomy: study with a minimum of ten years of follow-up. J Bone Joint Surg Am, 2004. 86(11): p. 2359-65.

8. Dargai, F., et al., Ten-year radiological and clinical outcomes of capitolunate arthrodesis with scaphoid and triquetrum excision for advanced degenerative arthritis in the wrist: Single-center, retrospective case series with 10patients. Hand Surg Rehabil, 2020. 39(1): p. 41-47.

9. Goubier, J.N., J. Vogels, and F. Teboul, Capitate pyrocarbon prosthesis in radiocarpal osteoarthritis. Tech Hand Up Extrem Surg, 2011. 15(1): p. 28-31.

10. Giacalone, F., et al., Resurfacing Capitate Pyrocarbon Implant versus Proximal Row Carpectomy Alone: A Comparative Study to Evaluate the Role of Capitate Prosthetic Resurfacing in Advanced Carpal Collapse. Plast Reconstr Surg, 2017. 140(5): p. 962-970.

11. Kistler, U., et al., Long-term results of silicone wrist arthroplasty in patients with rheumatoid arthritis. J Hand Surg Am, 2005. 30(6): p. 1282-7.

12. Peimer, C.A., et al., Reactive synovitis after silicone arthroplasty. J Hand Surg Am, 1986. 11(5): p. 624-38.

13. McCullough, M.B., B.D. Adams, and N.M. Grosland, Postoperative analysis of patients who received the Universal 2 total wrist implant system. J Appl Biomech, 2012. 28(4): p. 466-72.

14. Morapudi, S.P., et al., Total wrist arthroplasty using the Universal 2 prosthesis. J Orthop Surg (Hong Kong), 2012. 20(3): p. 365-8.

15. Ferreres, A., A. Lluch, and M. Del Valle, Universal total wrist arthroplasty: midterm follow-up study. J Hand Surg Am, 2011. 36(6): p. 967-73.

16. Zijlker, H.J.A., M. Ritt, and I.J. CB, Long-Term Results of Universal 2 Total Wrist Arthroplasty. J Wrist Surg, 2019. 8(4): p. 317-320.

17. Berber, O., L. Garagnani, and S. Gidwani, Systematic Review of Total Wrist Arthroplasty and Arthrodesis in Wrist Arthritis. J Wrist Surg, 2018. 7(5): p. 424-440.

18. Srnec, J.J., E.R. Wagner, and M. Rizzo, Total Wrist Arthroplasty. JBJS Rev, 2018. 6(6): p. e9.

19. Cooney, W., et al., Total wrist replacement: a retrospective comparative study. J Wrist Surg, 2012. 1(2): p. 165-72.

20. Shores, J.T., S. Demehri, and A. Chhabra, Kinematic "4 Dimensional" CT Imaging in the Assessment of Wrist Biomechanics Before and After Surgical Repair. Eplasty, 2013. 13: p. e9.

21. Demehri, S., et al., Evaluation of pisotriquetral motion pattern using four-dimensional CT: initial clinical experience in asymptomatic wrists. Clin Radiol, 2015. 70(12): p. 1362-9.

22. Garcia-Elias, M., X. Alomar Serrallach, and J. Monill Serra, Dart-throwing motion in patients with scapholunate instability: a dynamic four-dimensional computed tomography study. J Hand Surg Eur Vol, 2014. 39(4): p. 346-52.

23. Demehri, S., et al., Dynamic evaluation of pisotriquetral instability using 4-dimensional computed tomography. J Comput Assist Tomogr, 2014. 38(4): p. 507-12.

24. Mat Jais, I.S., et al., A method for carpal motion hysteresis quantification in 4-dimensional imaging of the wrist. Med Eng Phys, 2014. 36(12): p. 1699-703.

25. White, J., G. Couzens, and C. Jeffery, The use of 4D-CT in assessing wrist kinematics and pathology: a narrative view. Bone Joint J, 2019. 101-B(11): p. 1325-1330.

26. Carelsen, B., et al., Detection of in vivo dynamic 3-D motion patterns in the wrist joint. IEEE Trans Biomed Eng, 2009. 56(4): p. 1236-44.

27. Moojen, T.M., et al., In vivo analysis of carpal kinematics and comparative review of the literature. J Hand Surg Am, 2003. 28(1): p. 81-7.

28. Foumani, M., et al., In-vivo three-dimensional carpal bone kinematics during flexion-extension and radio-ulnar deviation of the wrist: Dynamic motion versus step-wise static wrist positions. J Biomech, 2009. 42(16): p. 2664-71.

29. Short, W.H., et al., The effect of sectioning the dorsal radiocarpal ligament and insertion of a pressure sensor into the radiocarpal joint on scaphoid and lunate kinematics. J Hand Surg Am, 2002. 27(1): p. 68-76.

30. Ruby, L.K., et al., Relative motion of selected carpal bones: a kinematic analysis of the normal wrist. J Hand Surg Am, 1988. 13(1): p. 1-10.

31. Klum, M., et al., Normative data on wrist function. J Hand Surg Am, 2012. 37(10): p. 2050-60.

32. Wolfe, S.W., C. Neu, and J.J. Crisco, In vivo scaphoid, lunate, and capitate kinematics in flexion and in extension. J Hand Surg Am, 2000. 25(5): p. 860-9.

33. Foumani, M., et al., The effect of tendon loading on in-vitro carpal kinematics of the wrist joint. J Biomech, 2010. 43(9): p. 1799-805.

34. Kobayashi, M., et al., Axial loading induces rotation of the proximal carpal row bones around unique screw-displacement axes. J Biomech, 1997. 30(11-12): p. 1165-7.

35. Gupta, A., Change of carpal alignment under anaesthesia: role of physiological axial loading on carpus. Clin Biomech (Bristol, Avon), 2002. 17(9-10): p. 660-5.

36. Malik, A.M., et al., MR imaging of the type II lunate bone: frequency, extent, and associated findings. AJR Am J Roentgenol, 1999. 173(2): p. 335-8.

37. Pang, E.Q., N. Douglass, and R.N. Kamal, Association of Lunate Morphology With Carpal Instability in Scapholunate Ligament Injury. Hand (N Y), 2018. 13(4): p. 418-422.
38. Rhee, P.C., S.L. Moran, and A.Y. Shin, Association between lunate morphology and carpal collapse in cases of scapholunate dissociation. J Hand Surg Am, 2009. 34(9): p. 1633-9.
39. Viegas, S.F., et al., Medial (hamate) facet of the lunate. J Hand Surg Am, 1990. 15(4): p. 564-71.
40. Nakamura, K., et al., Motion analysis in two dimensions of radial-ulnar deviation of type I versus type II lunates. J Hand Surg Am, 2000. 25(5): p. 877-88.
41. Abe, S., et al., Three-dimensional kinematics of the lunate, hamate, capitate and triquetrum with type 1 or 2 lunate morphology. J Hand Surg Eur Vol, 2018. 43(4): p. 380-386.

CHAPTER 9

Summary

Wrist osteoarthritis can lead to pain and loss of motion. Scaphoid Lunate Advanced Collapse (SLAC) and Scaphoid Nonunion Advanced Collapse (SNAC) are the most common patterns seen. Changes in the biomechanics of the proximal row due to the unrestrained (proximal part of the) scaphoid result in an abnormal motion pattern between the scaphoid and radius. Changes in motion patterns will eventually result in wrist osteoarthritis. This thesis aims to improve care (early diagnostics and treatment) for patients with wrist osteoarthritis.

Part 1 – Results after motion-preserving surgery in SNAC and SLAC wrists

In patients with chronic scapholunate ligament disruption or scaphoid nonunion, the abnormal motion pattern of the scaphoid results in progression of wrist osteoarthritis. SNAC and SLAC wrists can be classified into four stages: Stage 1 Osteoarthritis localized at the distal scaphoid and radial styloid, stage 2 osteoarthritis at the radioscaphoid joint, stage 3 osteoarthritis at the radioscaphoid joint and capitolunate joins, stage 4 osteoarthritis at the radiocarpal joint and intercarpal joints. The main goal of treatment is relieving pain while preserving wrist motion. Several motion-preserving techniques are available, but controversy still exists on which technique is superior for stage 2 SNAC and SLAC patients. Proximal row carpectomy (PRC) and four-corner fusion (FCF) are the two most commonly performed surgeries for stage 2 SNAC and SLAC wrists. During PRC surgery, the whole proximal row is removed, which results in a creation of a new radiocarpal joint. During FCF surgery the scaphoid is removed and the lunate, capitate, triquetrum and hamate are fused. For patients with stage 4 wrist osteoarthritis several generations of wrist implants are available. However, results of the latest "fourth generation" total wrist implants in patients with SNAC of SLAC are not known. In the first part, studies on outcomes of different motion-preserving techniques are presented.

Main findings

Chapter 2 Dynamic assessment of the wrist after proximal row carpectomy and four-corner fusion

- Flexion-extension of the wrist improves more after proximal row carpectomy than after four-corner fusion.
- Extension and ulnar deviation of the wrist are more limited after four-corner fusion than after proximal row carpectomy.
- Peak grip strength and area under the force-time curve are 80% compared to the contralateral unaffected wrist after proximal row carpectomy and 60% after four-corner fusion.

Chapter 3 Comparison of activities of daily living after proximal row carpectomy and four-corner fusion

- Overall activities of daily living are more quickly performed by patients after proximal row carpectomy relative to patients with four-corner fusion.
- Activities requiring wrist torque strength are more quickly performed by patients with four-corner fusion compared to patients after proximal row carpectomy.
- Patients after proximal row carpectomy reported better function during activities of daily compared to four-corner fusions patients.

Chapter 4 Results of the Universal 2 prosthesis in noninflammatory osteoarthritic wrists

- Universal 2 total wrist prosthesis gives satisfactory results in patients with end-stage noninflammatory wrist osteoarthritis.
- Range of motion and grip strength do not change after surgery compared to pre-operatively
- Patients reported improved DASH (disabilities of the arm, shoulder and hand) and VAS (visual analogue scale) scores after Universal 2 total wrist placement compared to pre-operatively

We concluded that for stage 2 SNAC and SLAC patients, both proximal row carpectomy and four-corner fusion provide good functional outcomes, range of motion and relief of pain. Overall, proximal row carpectomy patients have better postoperative results than four-corner fusion patients. In stage 4, the Universal 2 total wrist prosthesis showed that in noninflammatory osteoarthritis, the range of motion was preserved and pain was reduced.

Part 2 - Carpal kinematics

Early diagnosis of complex wrist injuries could result in earlier treatment and prevention of the development of wrist osteoarthritis. Understanding carpal kinematics helps recognising and diagnosing wrist injuries. In the second part of this thesis, we used the latest non-invasive method for analysing in vivo kinematics, the four-dimensional CT (4D-CT). The 4D-CT was used to establish a quantitative description of in vivo kinematics of the scaphoid, lunate and capitate in uninjured wrists. Our first aim was to establish test-retest reliability of the 4D-CT. Our second aim was to provide a better understanding of the effect of gender, hand dominance, axial force on carpal kinematics. These data may then serve as normative data for future studies on complex wrist injuries.

Main findings

Chapter 5 Quantifying in vivo scaphoid, lunate and capitate kinematics using four-dimensional computed tomography.

- 4D-CT scans reliably show in vivo carpal kinematics of uninjured wrists in healthy individuals.
- 4D-CT scans provide a unique data set of in vivo motion patterns of the scaphoid, lunate and capitate.

Chapter 6 Four-dimensional CT analysis of carpal kinematics: The effect of gender and hand-dominance.

- In males, hand-dominance has a significant effect on carpal kinematics.
- No differences in carpal kinematics were seen between the dominant and non-dominant hand in female individuals.
- Gender has no influence on carpal kinematics.

Chapter 7 – Effects of axial load on in vivo scaphoid and lunate kinematics using four-dimensional computed tomography.

- Applying axial load to the wrist results in:
  - a more flexed, radially deviated, and pronated position of the lunate and scaphoid during flexion-extension of the wrist.
  - a larger pronation and supination range of the lunate and scaphoid during flexion-extension of the wrist.
  - a larger flexion and extension range of the lunate and scaphoid during radial-ulnar deviation of the wrist.

In the **Chapter 8** of this thesis we discussed the main findings of the studies and compared them to the literature. We also made some suggestions for future research.

CHAPTER 10

Nederlandse samenvatting

Artrose van het polsgewricht kan leiden tot pijn en verlies van functie. Posttraumatische polsartrose wordt vooral gezien na ruptuur van het scapholunaire ligament (SLAC pols) of door een niet genezende fractuur van het scaphoid (SNAC pols). Door deze letsels ontstaan er veranderingen in de biomechanica van het polsgewricht. Deze veranderingen zorgen uiteindelijk voor slijtage van het gewricht. Het doel van dit proefschrift is om de zorg (eerdere/betere diagnostiek en behandeling) te verbeteren voor patiënten met posttraumatische polsartrose.

Deel 1 – Resultaten na behandeling van SNAC en SLAC polsen waarbij de beweging van het gewrichten behouden wordt

Bij patiënten met een langdurig bestaande ruptuur van het scapholunaire ligament of een niet genezende scaphoid fractuur ontstaat er door een abnormaal bewegingspatroon van het scaphoid en het lunatum een progressief, volgens een vast patroon verlopende artrose van het polsgewricht. Deze artrose kan worden in gedeeld in 4 stadia: Stadium 1 Artrose ter plaatse van het distale deel van het scaphoid en processus styoloideus radii, stadium 2: artrose ter plaatse van het radioscaphoid gewricht, stadium 3: artrose ter plaatse van het radioscaphoid gewricht en het capitolunatum gewricht en stadium 4: artrose ter plaatse van het radiocarpale gewricht en de intercarpale gewrichten. Doel van de behandeling is om de pijn die patiënten ervaren te verminderen terwijl de beweging in het pols gewricht zo veel mogelijk behouden blijft. Verschillende technieken om de beweging te behouden zijn mogelijk, maar er is nog veel discussie over welke techniek het meest geschikt is voor stadium 2 SLAC en SNAC patiënten. Proximale rij carpectomie (PRC) en four corner fusie (FCF) zijn de twee meest uitgevoerde operaties voor stadium 2 SNAC en SLAC polsen. Bij een PRC wordt de gehele proximale rijd verwijderd wat resulteert en een nieuw radiocarpaal gewricht. Bij FCF wordt het scaphoid verwijderd en vervolgens het lunatum, capitatum, triquetrum en hamatum gefuseerd waardoor het originele radiocarpale gewricht blijft bestaan. Voor stadium 4 polsartrose zijn verschillende generaties polsimplantaten beschikbaar. Echter, de resultaten van de laatste "4^{e} generatie" prothese zijn alleen beschreven in patiënten met reumatoïde artritis en niet bij posttraumatische polsartrose. In het eerste deel, hebben we gekeken naar de resultaten van verschillende "bewegingsbehoudende" behandeltechnieken van voor patiënten met posttraumatische polsartrose.

Voornaamste bevindingen

Hoofdstuk 2 Dynamisch onderzoek van de pols na proximale rij carpectomie en four-corner fusie

- *Flexie-extensie van het polsgewricht verbetert meer na proximale rij carpectomie dan na four-corner fusie*
- *Extensie en ulnair deviatie van het polsgewricht is meer beperkt na four-corner fusie dan na proximale rij carpectomie*
- *Piek knijpkracht en gebied onder de knijpkracht curve zijn 80% ten opzichte van de contralaterale, niet aangedane pols na proximale rij carpectomie en 60% na four-corner fusie.*

Hoofdstuk 3 Vergelijking van de polsfunctie in het dagelijks leven na proximale rij carpectomie en four-corner fusie

- Over het algemeen worden activiteiten in het dagelijks leven sneller uitgevoerd door patiënten met een proximale rij in vergelijking met patiënten four-corner fusie.
- Activiteiten waarbij krachtige torsie nodig is worden sneller uitgevoerd door patiënten met een four-corner fusie in vergelijking met patiënten met een proximale rij carpectomie.
- Patiënten rapporteren na een proximale rij carpectomie een betere polsfunctie gedurende algemeen dagelijks leven in vergelijking met patiënten na een four-corner fusie.

Hoofdstuk 4 Resultaten van de Universal 2 polsprothese in patiënten met posttraumatische polsartrose.

- De resultaten van de Universal 2 totale polsprothese zijn acceptabel in patiënten met eind stadium posttraumatische polsartrose.
  - Het bewegingsbereik en de knijpkracht van de hand/pols veranderen postoperatief ten opzichte van preoperatief.
  - Patiënten rapporteren een verbeterde handfunctie postoperatief ten opzichte van peroperatief.

Wij concludeerden dat voor stadium 2 SNAC en SLAC patiënten de resultaten na zowel de proximale rij carpectomie als de four-corner fusie voldoende zijn wanneer gekeken wordt naar de functionele uitkomsten, het behoud van beweging en vermindering van de pijn. Over het algemeen zijn de resultaten na een proximale rij carpectomie beter dan na een four-corner fusie. De resultaten van de Universal 2 polsprothese voor stadium 4 SNAC en SLAC patiënten lieten een behoud van polsfunctie en vermindering van pijn zien.

Deel 2 - Carpale kinematica

Vroege diagnostiek van complexe pols letsels resulteert in eerdere behandeling en preventie van het ontstaan van polsartrose. Kennis van de carpale kinematica helpt bij het herkennen en diagnosticeren van polsletsels. In het tweede deel van dit proefschrift maakten wij gebruik van de nieuwste niet-invasieve methode om de carpale kinematica in kaart te brengen, de vier dimensionale CT (4D-CT). De 4D-CT werd gebruikt om op een zo nauwkeurig en kwantitatieve mogelijke manier de kinematica van het scaphoid, lunatum en capitatum in niet aangedane polsen te beschrijven. Ons eerste doel was om de test-hertest betrouwbaarheid van deze methode vast te stellen. Het tweede doel was om een gedetailleerde beschrijving te geven van het effect van geslacht, handdominantie, en axiale kracht op de carpale kinematica. Deze data kunnen vervolgens dienen als normatieve data voor toekomstige studies naar complexe polsletsels.

Voornaamste bevindingen

Hoofdstuk 5 Kwantificeren van in vivo kinematica van het scaphoid, lunatum en capitatum doormiddel van vierdimensionale CT.

- De 4D-CT scan beschrijft betrouwbaar in vivo carpale kinematica bij niet-aangedane polsen van gezonde vrijwilligers
- 4D-CT scans leveren een unieke dataset van in vivo bewegingspatronen van het scaphoid, lunatum en capitatum.

Hoofdstuk 6 Vierdimensionale CT analyse van de carpale kinematica: het effect van geslacht en handdominantie.

- Bij mannen heeft de handdominantie een significant effect op carpale kinematica.
- Er werden geen verschillen in bewegingspatronen gezien tussen de dominante hand en niet-dominante hand bij vrouwen.
- Geslacht heeft geen invloed op carpale kinematica.

Hoofdstuk 7 Effect van axiale kracht op in vivo kinematica van het scaphoid en lunatum doormiddel van vierdimensionale CT.

- Toevoegen van axiale kracht op het polsgewricht resulteert in:
  - Een meer geflecteerde, meer radiaal gedevieerde en een toegenomen pronatie van het lunatum en scaphoid tijdens flexie en extensie van de pols.
  - Meer pronatie en supinatie reikwijdte van het lunatum en scaphoid tijdens flexie en extensie van de pols.
  - Meer flexie en extensie reikwijdte van het lunatum en scaphoid tijdens radiaal en ulnair deviatie van de pols.

In **Hoofdstuk 8** van dit proefschrift bespreken we de voornaamste bevindingen van de verschillende studies en vergelijkingen wij ze met de resultaten en bevindingen beschreven in de literatuur. Daarnaast geven wij enkele suggesties voor toekomstig onderzoek.

APPENDICES

List of publications

PhD Portfolio

Curriculum Vitae

Dankwoord

List of publications

Dynamic assessment of wrist after proximal row carpectomy and 4-corner fusion.
Singh HP, **Brinkhorst ME**, Dias JJ, Moojen T, Hovius S, Bhowal B.
J Hand Surg Am. 2014;39(12):2424-2433.

Comparison of activities of daily living after proximal row carpectomy or wrist four-corner fusion.
Brinkhorst ME, Singh HP, Dias JJ, Feitz R, Hovius SER.
J Hand Surg Eur Vol. 2017;42(1):57-62

Results of the Universal 2 Prosthesis in Noninflammatory Osteoarthritic Wrists
Brinkhorst ME, Selles RW, Dias JJ, Singh HP, Feitsz R, Moojen TM, Hovius SER..
J Wrist Surg. 2018;7(2):121-126.

Comparing radial styloid size between osteoarthritic and healthy wrists: a pathoanatomical three-dimensional study.
Ten Berg PWL, Dobbe JGG, **Brinkhorst ME**, Strackee SD, Streekstra GJ.
J Hand Surg Eur Vol. 2017;42(1):63-70.

Scaphoid screw fixation perpendicular to the fracture plane: Comparing volar and dorsal approaches.
Ten Berg PWL, Dobbe JGG, **Brinkhorst ME**, Meermans G, Strackee SD, Verstreken F, Streekstra GJ.
Orthop Traumatol Surg Res. 2018;104(1):109-113.

A four-dimensional-CT study of in vivo scapholunate rotation axes: possible implications for scapholunate ligament reconstruction.
de Roo MGA, Muurling M, Dobbe JGG, **Brinkhorst ME**, Streekstra GJ, Strackee SD.
J Hand Surg Eur Vol. 2019;44(5):479-487.

Effects of axial load on scaphoid and lunate kinematics in uninjured wrists using four-dimensional CT.
Brinkhorst ME, Streekstra GJ, van Rosmalen J, Strackee SD, Hovius SER.
J. Hand Surg Eur Vol. 2020 Nov;45(9):974-980.

Quantifying in vivo scaphoid, lunate, and capitate kinematics using four-dimensional computed tomography
Brinkhorst ME, Foumani M, van Rosmalen J, Selles RW, Hovius SER, Strackee SD, Streekstra GJ.
Skeletal Radiol. Vol. 2021 Feb; 50(2):351-359.

The effect of gender and hand-dominance on carpal kinematics in healthy volunteers using four-dimensional computed tomography.
Brinkhorst ME, Streekstra GJ, van Rosmalen J, Strackee SD, Hovius SER.
Submitted

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PhD Portfolio

Name PhD candidate:	Michelle Esther Brinkhorst
Erasmus MC department:	Plastic and Reconstructive Surgery
Research school:	NIHES
PhD period:	2012 – 2021
Promotoren	Em.prof.dr. S.E.R. Hovius
	Prof.dr. R.W. Selless
Co-promotor:	Dr.ir. G.J. Streekstra

PhD training

	Year	Workload
General academic skills		
• NIHES Master of Clinical Epidemiology	2012-2014	60 ECTS
General courses		
• Teach the Teacher 1, *Erasmus MC*	2018	2 ECTS
• BROK and Good Clinical Practice, *Erasmus MC*	2014	30 hrs
• Research Integrity, *Erasmus MC*	2014	0.3 ECTS
• Biomedical English Writing and Communication Course, *Erasmus MC*	2013	4 ECTS
Specific courses		
• Stralingshygiëne, *Erasmus MC*	2014	1 ECTS
• Microsurgery training. Skillslab *Erasmus MC*.	2012-2014	210 hrs
• Workshop Tendon reconstruction. Skillslab *Erasmus MC*	2013	0.2 ECTS
• Workshop Nerve reconstruction. Skillslab *Erasmus MC*	2013	0.2 ECTS
• Workshop local transposition flaps. Skillslab *Erasmus MC*	2013	0.2 ECTS

Presentations

• ASSH meeting. Posterpresentation : "Results of the Universal-2 total wrist arthroplasty in patients with post-traumatic wrist osteoarthritis" *Boston, USA*	2014	20 hrs
• Najaarsvergadering NVPC. "Resultaten van de Universal 2 pols prothese bij patienten met posttraumatische polsartrose". *Amsterdam.*	2014	20 hrs
• FESSH meeting. "Timed Sollerman hand function test: Proximal Row Carpectomy versus Four-corner fusion". *Antalya, Turkey*	2013	20 hrs

Conferences attendance

• NVPC Scientific Meeting, Multiple locations	2012-2014 2017-2020	2 ECTS
• Kortjakje Zondagschool voor Plastische Chirurgie Kasteel Kerckebosch, *Zeist*	2013/2020	0.3 ECTS
• FESSH meeting, *Milan, Italy*	2015	1 ECTS

Teaching and Lecturing

	Year	**Workload**
Lecturing		
• Refereeravond "Research Integrity" *Erasmus MC*	2014	0.3 ECTS
• Anatomie van de hand 3e jaars studenten. Snijzaal *Erasmus MC*	2013-2014	0.3 ECTS
• Introductie plastische chirurgie 2e jaars keuze onderwijs. Onderwijscentrum *Erasmus MC*	2014	0.3 ECTS

Supervising practicals, Tutoring

• Supervising microsurgery course. Skillslab *Erasmus MC*	2013-15	50 hrs
• Supervising minor students *Erasmus MC*	2013	60 hrs

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Other

• Board Member Junior Vereniging Plastische Chirurgie (JVPC)	2019 - 21	3 ECTS
• Supervision and editor book: Compendium Geneeskunde part Plastic Surgery	2019	120 hrs
• Organizing 23rd Esser Course On your nerves	2014	2.5 ECTS
• Organizing 22nd Esser Course Breast reconstruction	2014	2.5 ECTS
• Organizing 21st Esser Course Wide Awake surgery	2013	2.5 ECTS

Curriculum Vitae

Michelle Esther Brinkhorst was born on September 5th 1986 in Enschede, the Netherlands. As the middle child of three, she grew up in Gabon, Nigeria and eventually the Netherlands. After graduating from the gymnasium at the Bonhoeffer college in Enschede in 2004, she started medical school at the University of Groningen. Throughout medical school she developed a great interest in plastic and reconstructive surgery. In 2011 Michelle received her medical degree and started working as a senior house officer in plastic and reconstructive surgery at the Diakonessenhuis in Utrecht and Zeist (drs. R.F. Feitz). From January 2012 till August 2012 she worked as a senior house officer at the plastic and reconstructive surgery department at the Erasmus University Medical Center (dr. L.N.A. van Adrichem).

In August 2012 she started her PhD project resulting in this thesis at the plastic surgery department at the Erasmus University Medical Center (Prof.dr. S.E.R. Hovius), which was granted by NutsOhra. In September 2012 Michelle enrolled in a second master's program Clinical Epidemiology at the Netherlands Institute for Health Sciences (NIHES).

In December 2014 she started her residency in plastic surgery at the general surgery department of the Haaglanden Medical Center (HMC) in The Hague (dr. H.J. Smeets). In April 2017 Michelle returned to the plastic and reconstructive department of the Erasmus University Medical Centre (dr. A.J.M. Luijsterburg) to continue her plastic surgery training. Since January 2019 she is a board member of the Junior Society of Plastic Surgeons (JVPC).

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