01 May 2017

Common Treatments and Procedures Used for Fractures of the Distal Radius and Scaphoid: A Review

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Materials Science and Engineering C 74 (2017) 422–433

Contents lists available at ScienceDirect

Materials Science and Engineering C

journal homepage: www.elsevier.com/locate/msec

Common treatments and procedures used for fractures of the distal radius and scaphoid: A review

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ARTICLE INFO

Article history:
Received 16 August 2016
Accepted 8 December 2016
Available online 9 December 2016

ABSTRACT

The distal radius and the scaphoid are the most commonly injured carpal bones among both active adults and the osteoporotic elderly. The purpose of surgical treatment is to restore form and function to the wrist. Depending on the nature of the fracture, either topical procedures or invasive surgery can be applied. This article critiques the treatments currently used for fixation of wrist fractures in order to drive the development of new materials to improve patient outcomes.

Contents

1. Introduction

A wrist fracture can occur as a result of trauma. They are common at any age, however those who suffer from osteoporosis are at higher risk of experiencing a fracture [1]. Fractures of the distal radius and scaphoid are the most common. There has been an increase in surgical fixation of fractures involving the distal radius and scaphoid due to increased patient expectation and the development of fixation techniques [2]. The objective of this review is to identify the outages in the materials and techniques currently used for treatment of wrist fractures in order to facilitate the development of new materials and techniques, which may improve patient outcomes.

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http://dx.doi.org/10.1016/j.msec.2016.12.038

1.1. Anatomy of the wrist

The wrist or carpus (Fig. 1) is a multifaceted joint located between the five metacarpal bones of the hand and the radius and ulna bones of the forearm. It also includes eight small carpal bones that are positioned in two rows (proximal and distal) [3]. Located in the proximal row are the lunate, triquetral and pisiform bones; the distal row consists of the trapezium, trapezoid, capitate, and hamate bones [4]. However, the largest carpal bone is the scaphoid, which extends across both the proximal and distal rows [4]. Additionally, the wrist includes many component joints, listed below [3]:

- Distal radio-ulnar joint (performs as a pivot for the bones in the forearm)
- Radiocarpal joint (located among the radius and the bones located in the proximal row, in charge of wrist flexion and extension)
- Midcarpal joint (located between the proximal and distal rows of carpal bones)
- Various intercarpal joints (between adjacent carpal bones within the rows)

The flexibility and range of motion of the wrist can be attributed to the many bones and their multifaceted articulations. The radioulnar joint is detached from the wrist joint by a fibrocartilaginous disk, located between the radius and the ulna [3]. The radiocarpal ligaments are responsible for rotational movements of the hand and the forearm, while the intercarpal ligaments are responsible for strengthening the small wrist bones [3].

2. Common wrist fractures

The radius and the scaphoid are the two wrist bones that most commonly fracture.

2.1. Causes of wrist fractures

The most common cause of both scaphoid and distal radius fracture is when an individual has fallen onto an outstretched hand in order to break their fall [5].

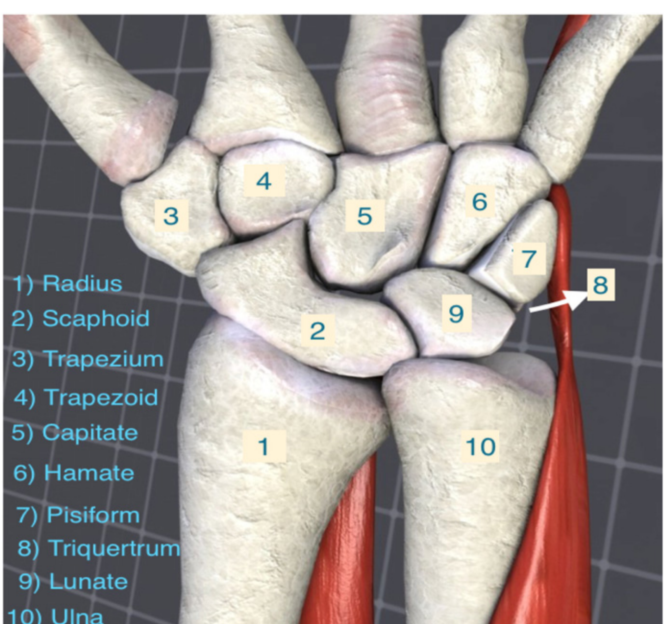


Fig. 1. Illustration of the eight carpal bones and two long bones (radius and ulna) of the wrist.

2.2. Distal radius fracture

The radius can fail in various ways; the most common distal radius fracture is called the Colles fracture, which is when the broken piece of the radius is tilted upwards (Fig. 2) [5]. This type of fracture tends to occur about 1 in. from the end of the bone [5]. A less common fracture of the radius is the reverse Colles fracture (Smith's fracture); which is when the back of the wrist is the first to break the fall, forcing the hand under the wrist (Fig. 2) [6]. If a distal radius fracture is left untreated, it could lead to soft tissue damage and late development of carpal tunnel syndrome, which is a painful condition resulting from compression of the median nerve [7]. The most common complication of a distal radius fracture is malunion, when the fractured bone has healed in a deformed position, resulting in pain, loss of grip strength and limited wrist mobility [5].

2.3. Scaphoid fracture

The scaphoid fracture involves a break in one of the 8 small carpal bones located at the wrist. The scaphoid is required for stability and coordination [5]. Such fractures account for roughly 60% of all carpal fractures [9]. A scaphoid fracture is most seen in active young adults and the elderly. It often occurs when the hand is breaking a fall (Fig. 3). It is common for scaphoid fractures to go unrecognized or misdiagnosed as a wrist sprain [5]. Scaphoid fractures, if untreated, could develop nonunion (bone which does not heal properly) or malunion (bone which heals in the wrong position), which can ultimately leading to carpal arthritis, decreased range of motion and grip strength [9]. Avascular necrosis is also a concern of scaphoid fractures, when blood supply to the bone is interrupted due to the fracture; it eventually leads to the disruption of the healing process [10].

2.4. Risk factors

Young adolescents and adults who participate in intense activities as well as the elderly are at risk of developing scaphoid fractures and distal radius fractures [12]. Also, if individuals suffer from osteoporosis, have low muscle mass, poor muscle strength or lack agility then they are also at risk of having wrist fractures [1].

3. Treatment and procedures

3.1. Distal radius fracture: non invasive surgery

A cast constructed of plaster (Fig. 4) is usually the most common option if the patient has a non-displaced fracture. The cast remains until the bone is healed. If the alignment of the bone is not optimal, the surgeon will perform re-alignment of the broken bone (referred to as reduction) [13]. A closed reduction is when the surgeon is not required to make an incision and yet is still able to straighten the bone [13]. Once proper alignment of the bone is achieved, the patient's arm is covered in a splint/cast. A splint is first used to allow for normal swelling associated to the fracture, while a cast is placed after the swelling has decreased [13]. Patients are given regular x-rays to monitor the healing of the fracture. The cast is typically removed after six weeks from the date of the fracture [13]. During this time, physical rehabilitation usually begins to assist in improving the movement and function of the healing wrist.

3.1.1. Distal radius fracture: minimally invasive surgery

Surgery may be necessary when the position of the broken bone is so displaced that nonsurgical techniques are not an option. Surgical treatment usually applies open reduction where an incision is made in order to provide entry to the broken bone in hopes of improving alignment [13]. Other surgical treatment includes [15]:

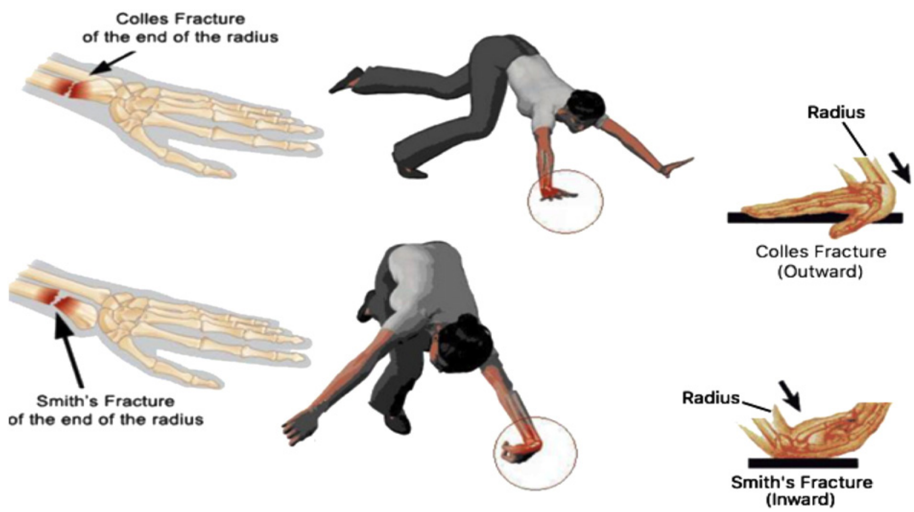


Fig. 2. Depiction of the position of the wrist at the time of falling and the bones affected by the Colles fracture and the Smith's fracture, adapted from [8].

- Internal fixation: (stainless steel or titanium pins, plates, screws)
- External fixation (a stabilizing frame outside the body that holds the bones in the proper position so they can heal)
- Percutaneous fixation (pins and casting)
- Any combination of these techniques

3.1.1.1. Internal fixation. An incision is performed above the fracture; a stainless steel plate is applied and secured with screws directly to the bone in order to achieve proper alignment [15]. In this case, the plate is used in order to avoid future displacement of the fractured bone. Benefits of internal fixation include an increase in stability, precise placement of the implant, no need for external devices, no interference of casts and, possibly, a faster healing time. Patients may experience an improvement in the movement of their wrist one-two weeks following internal fixation; at this point a temporary splint is used in order to provide support for the hand [15]. Rozental & Blazer [16] observed 41 patients who had been treated with volar fixed-angle plating for dorsally displaced, unstable distal radius fractures in order to determine their functional outcome. Volar locking plates were utilized in order to stabilize the fractures. Radiographs portrayed a mean radial height of 11 mm, a mean radial incline of 21° and a mean volar tilt of 4° (Fig. 5) [16]. Results of this study showed complications after surgery in nine patients; four experienced loss of reduction (failure to keep the fracture correctly aligned) with fracture collapse; removal of hardware was needed for three patients due to tendon inflammation; one patient suffered from a wound rupture along the surgical incision and one patient presented with stiffness in the metatarsophalangeal joint [16]. Regardless, patients in this study exhibited good or excellent functional outcome, while reporting that their symptoms partially or completely improved once the hardware was removed [16].

Early complications of volar locking plate fixation of distal radius fractures were evaluated by Ward et al. [17]. 92 patients were observed; open reduction and internal fixation of 96 distal radius fractures were performed using a volar locked plate. Results showed that 22 complications emerged in 21 of the 92 patients. Carpal tunnel syndrome (CTS) was present in three patients, resulting in the need for carpal tunnel release; nine patients reported incidences of paresthesias or numbness. Additionally, three patients suffered from superficial pin tract infections, which were eventually healed with oral antibiotics and the removal of the pin [17].

3.1.1.2. Percutaneous fixation. This type of fixation is simple and tends to only involved pins and casts with some incision, and can be performed in the operating room using local anesthetics [15]. Once percutaneous fixation is performed, a cast is applied to the patient. Upon healing of the fracture, the pins are removed in order to allow the patient to undergo physical rehabilitation. Benefits of percutaneous pin fixation include sufficient stability for closed reduction, no requirements for permanent hardware, minimal soft tissue complications, reduced pain from surgery, and no surgical incision [13]. Lakshmanan et al. [18] observed 43 patients who experienced closed reduction and percutaneous Kirschner wire (K-wire) fixation for unstable distal radius fracture. Two to three K-wires of 1.6 mm diameter were used to secure every fracture. An incision was made with a #15 knife blade in order to allow the insertion of each K-wire [18]. Once inserted, the K-wires were left sticking out of the skin to ensure easy removal by the surgeons. In order to avoid

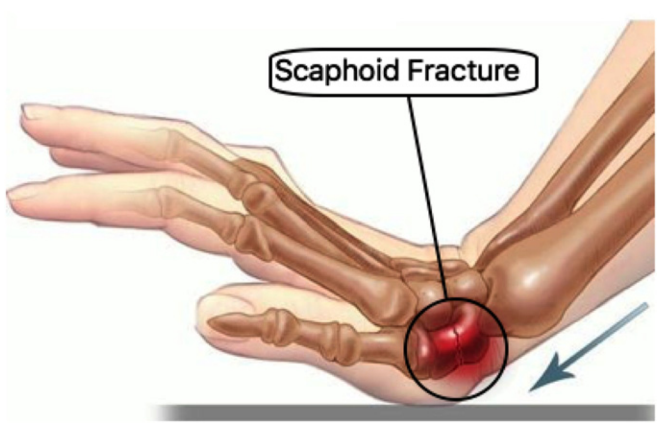


Fig. 3. Position of the wrist during a scaphoid fracture and the bone that is affected by a scaphoid fracture, adapted from [11].

Fig. 4. A plaster cast typically used for nonsurgical treatment, adapted from [14].

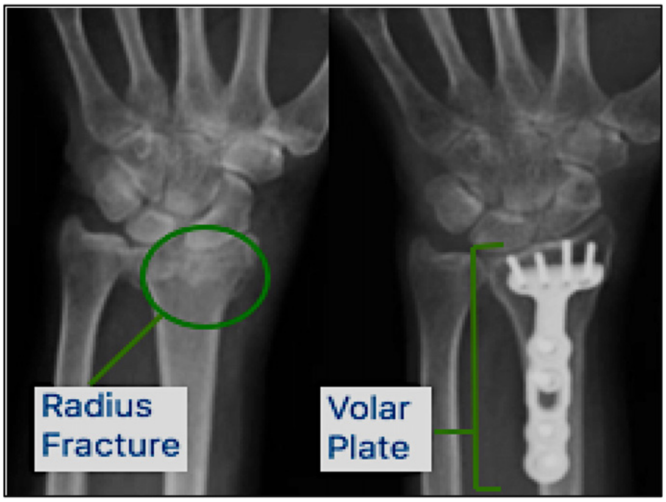


Fig. 5. Left to right, preoperative radiograph showing distal radius fracture and postoperative radiograph with volar plate, adapted from [16].

movement of the K-wires, the ends were bent towards the outside of the skin. A plaster cast was applied to the fracture. Follow up was given at one, two, four and six weeks following the procedure. Pin tract infection was present in nine out of the 43 patients, while three patients required earlier removal of the K-wires during week three [18]. A prospective study presented by Chen et al. [19] on 54 patients experiencing distal radius fracture which had been treated with percutaneous K-wire fixation and pin-in-plaster technique. Patients were provided treatment during a one-year period. The majority of these patients suffered fractures from falling (36), while the remaining fractures were a result of traffic accidents (18). It was noted that 28 of the patients had fractures in the left wrist, while 26 patients had fractures in the right. Once reduction was performed, two percutaneous K-wires were inserted and drilled proximally through the radial styloid [19]. Upon completion of percutaneous pinning, two K-wires were inserted, one at the base of the second metacarpal bone and one into the junction of the distal and middle thirds of the radial shaft [19]. To prevent exterior mobilization, a securely fit pin-in-plaster was then applied. Results indicated that bony union was attained in all patients (Fig. 6a–c) [19]. Patients also reported a 90.7% satisfaction in their ability to perform pre-injury activities, however two patients suffered pin tract infection, requiring the removal of the pin-in-plaster earlier than anticipated [19]. It was suggested by Chen et al. [19] that the pin-in-plaster provided sufficient stability during fracture healing.

3.1.1.3. External fixation. This technique requires the implementation of an external frame (Fig. 7 a-b), which holds the broken bone in place with the use of pins [13]. Surgeons use percutaneous pins with the combination of the external frame with the intent to support the bone fragments. Upon construction of the external frame, patients are able to easily move their fingers around, allowing them to perform lightweight duties [13]. Three to six weeks following the surgery, the surgeon removes the pins. Benefits of external fixation are minimum disruption of soft tissue, temporary hardware, and minimal scarring after the incision [13].

3.2. Scaphoid fracture

3.2.1. Non invasive surgery

Scaphoid fractures can be healed with a thumb spica splint cast, which immobilizes the elbow, wrist and thumb for six weeks; afterwards the wrist and thumb will be immobilized for another six weeks [22]. The thumb spica splint cast must be regularly checked to confirm fit so that movement is prohibited. Once the cast is removed, the patient undergoes rehabilitation in order to aid in restoring the range of motion and strength of the wrist [22]. There are low risks associated to casts: skin irritations, itching, muscle atrophy and stiffness are the most common [22]. More serious complications could involve skin pressure sores and cutaneous nerve compression with transient numbness [23].

3.2.2. Minimally invasive surgery

Surgical treatment is necessary when a scaphoid bone is broken at the scaphoid waist or proximal pole. Surgical treatments include [24]:

- Reduction
- Internal fixation
- Bone graft

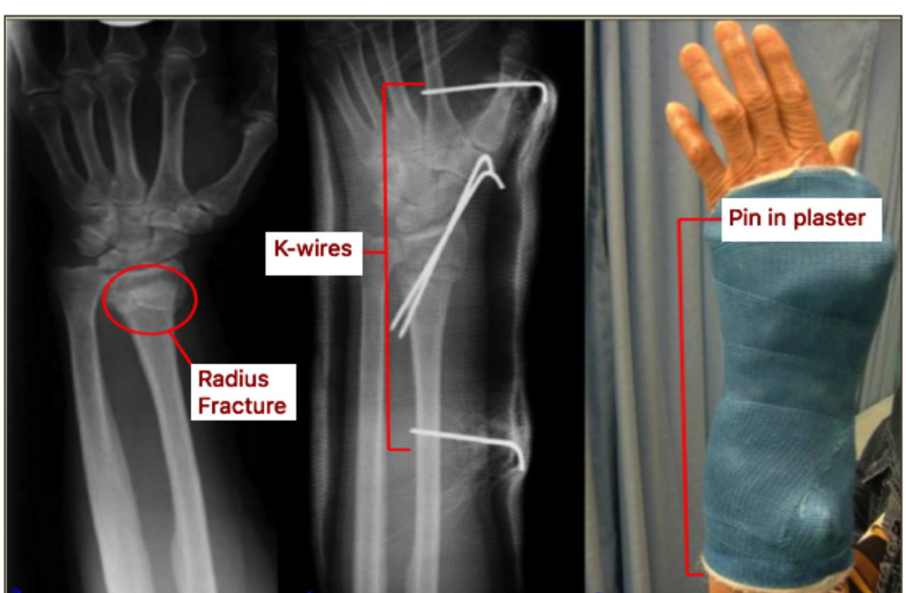


Fig. 6. a) Preoperative radiograph showing distal radius fracture in study patient, b) postoperative radiograph with K-wires, c) photograph of study patient's fracture fixation with pin-in-plaster, adapted from [19].

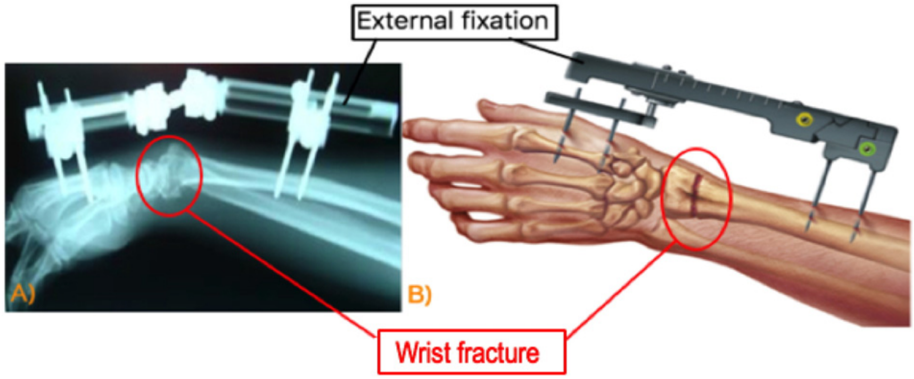


Fig. 7. A) Radiograph of an external fixation device after implantation, adapted from [20]. B) Illustration of external fixation device positioned in order to immobilize the broken bone, adapted from [21].

3.2.2.1. Reduction. Patients are given an anesthetic and the surgeon manipulates the bone back into the proper position. In some cases, it is done through an open incision with direct manipulation of the fracture [25]. A study was performed on 14 patients that presented acute displaced scaphoid waist fractures (Fig. 8), which had been treated by open reduction and internal fixation [26]. Fixation was performed in eight of the 14 patients using Herbert compression screw and K-wires were used in six of the 14 patients [26]. Ten patients also underwent supplemental radial bone graft due to fracture comminution (Fig. 9) [26]. Upon completion of surgery, all patients were splinted and a thumb spica cast was applied until union. Upon removal, patients underwent occupational therapy in order to restore wrist range of motion (ROM) and grip strength [26]. Follow up occurred 26 months after surgery, when it was found that 13 out of the 14 fractures had united and there was great improvement in the patient's wrist ROM (wrist extension 57°, wrist flexion 52°) and grip strength [26]. Radiographic evaluation indicated that scaphoid fractures had healed, intrascaphoid alignment was restored and there was no evidence of carpal instability [26].

3.2.2.2. Internal fixation. This technique involves surgeons using metal implants (wires and screws) to correct and stabilize the scaphoid in the correct position until completely healed [25]. The location and size of the incision will depend on where the scaphoid bone has broken. At times, the screw or wire is placed in a bone fragment with a small incision, in other cases, a larger incision is required to ensure that the fragments of the scaphoid line up properly [25]. The incision may be made on either the front or back of the wrist. Risks with this technique include stiffness, infection, nerve injury and the potential for nonunion, resulting in the possibility of re-operation [23]. Dias et al. [27] observed 88 patients in a prospective randomized study, which had acute nondisplaced or minimally displaced fractures of the waist of the scaphoid. Results indicated that there was an early return of ROM and grip strength after open reduction and internal fixation was temporary yet the surgical complication rates were high [27]. These complications included scars ($n = 10$), a wound infection ($n = 1$), a nerve injury ($n = 1$) and algodystrophy (pain, swelling and stiffness of the affected area; $n = 1$) [27,28]. It was concluded that early internal fixation presented no clear benefit over nonsurgical cast immobilization for patients with acute nondisplaced or minimally displaced fractures [29].

3.3. Bone grafts for wrist fracture treatment

In some situations a bone graft might be used with or without internal fixation, specifically when the bone is broken into two or more pieces in order to promote appropriate healing. Grafting involves new bone being positioned around the broken distal radius bone or scaphoid bone in order to accelerate the healing process while allowing bone production [25]. The bone graft can be taken from the patients forearm bone in the same arm or from the iliac crest [25]. Bone graft materials can be osteogenic (occurrence of bone forming tissues), osteoconductive (bone growth on a surface) and osteoinductive (promoting development of bone). In order for a bone graft material to be optimal it must promote bone restoration, offer stability, be biocompatible and bioresorbable and be cost efficient.

3.3.1. Autograft

Autogenous bone grafts (harvested from other parts in the body), are typically used due to tissue compatibility, their ability to offer the greatest osteoconductive, osteogenic and ostoeinductive properties

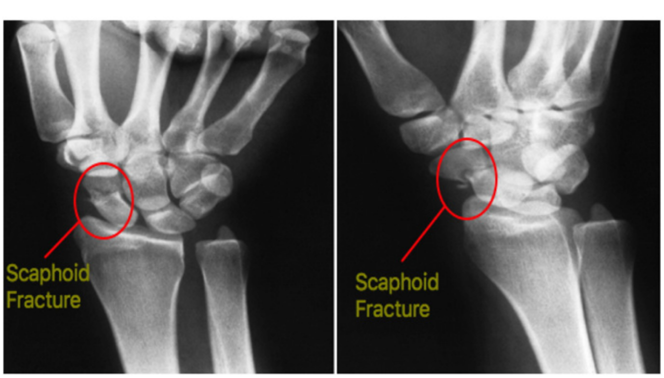


Fig. 8. Radiographs of an acute displaced scaphoid wrist fracture prior to surgery, adapted from [26].

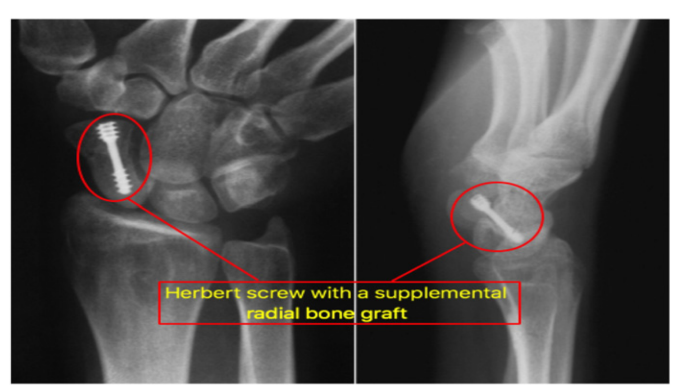


Fig. 9. Radiographs of scaphoid wrist fracture after open reduction and internal fixation utilizing Herbert screw with a supplemental radial bone graft, adapted from [26].

and ability to provide structural support [30–32]. However, autogenous bone grafts can also be affected by resorption. These are commonly taken from the iliac crest of the patient, but small amounts may be removed from the tibial crest and olecranon [33–41]. Diaz & Chang [42] presented a case of a 22-year-old male mountain biker who endured a fracture of the scaphoid on his left wrist. The patient had been originally treated with cast immobilization for duration of four weeks, however he developed a scaphoid nonunion that was then treated with open reduction and internal fixation using distal radius bone graft [42]. After complaining of pain for two years following his fall, CT scans were performed, showing nonunion of the scaphoid and humpback deformity (an increase in angulation between the proximal and distal sections of the scaphoid). It was decided that hardware removal and revision open reduction internal fixation with iliac crest bone graft was the best option [42]. Results indicated that the patient's range of motion and strength two years and five months post revision surgery was comparable to that of his right wrist. The authors suggest that the use of iliac crest bone graft was suitable for surgical revision of the humpback deformity of the scaphoid [42]. Despite showing suitable results obtained from radiographs and wrist function, bone grafts taken from the iliac crest have been found to cause pain in the donor site, hematoma (swelling of blood clots in tissues), neuroma (growth or tumor of nerve tissue), infection and morbidity [43–47]. Due to the cost of rehabilitation treatment, pain management and time from work, iliac crest was no longer considered a cost effective bone graft [48–51].

3.3.2. Allograft

Allograft bone (harvested cadaver bone) possesses osteoconductive and osteoinductive properties. Allograft bone can be offered in different shapes and sizes, they are less likely to be associated to any morbidity at the donor site as they are harvested through bone banks, but it is not as structurally stable as the autogeneous bone graft. A study was conducted by Herrera et al. [52], where 17 patients with unstable distal radius fractures experienced external fixation using freeze-dried cancellous allogenic bone graft. It was reported that three patients had full mobility of their wrist, 13 reported only 75% mobility of their wrist and 99% of range of motion and one reported 53% of range of motion [52]. Following surgery there were reports of two cases of pin tract infection that resulted in the removal of fixator and one case of a broken K-wire embedded in the distal ulnar head (asymptomatic) [52]. However results indicated that at eight weeks follow up, complete incorporation of the bone graft occurred and there was no loss of reduction [52]. A randomized study by Rajan et al. [53] considered 90 patients with large metaphyseal defects in order to compare allograft bone chips with iliac crest bone grafts. Results indicated that there was no statistical variance between the two groups in regards to their functional performance, however the iliac crest bone graft group presented higher percentage of morbidity at the donor site, lengthy surgical procedures and greater cost of treatment [53]. It was determined that in regards to treatment of distal radius fractures allograft was a suitable replacement for iliac crest bone grafts [53].

3.3.3. Substitutes

Since complications are associated with both autografts and allografts, bone grafts from other, non-human, sources have been used for the purposes of promoting bone healing.

3.3.3.1. Biological grafts

3.3.3.1.1. Coralline hydroxyapatite. Regardless of coral's natural appearance, it does not go through osteoclastic resorption with ease and is visible on radiographic imaging for extended periods of time. Wolfe et al. [54] treated 21 consecutive patients with distal radius fractures using implanted coralline hydroxyapatite (HA) bone graft with external fixation and K-wires in order to examine the efficacy and complications in supporting the reduced articular surface. Complications were reported in ten patients; one was specifically associated with the use of the coral [54]. However, for the most part, implanted coralline (HA) was a safe and effective choice as a bone graft substitute and maintained articular surface reduction when combined with external fixation and K-wires [54].

3.3.3.1.2. Demineralized bone matrix. Demineralized bone matrix is a result of processed allograft bone that has been demineralized in order to extract proteins that promote formation of bone. It is an osteoinductive and osteconductive material that does not provide structural strength to an articular surface [55–59]. Demineralized bone matrix can be typically used in stabilizing bone defects in order to promote bone recovery.

3.3.3.2. Synthetic grafts

3.3.3.2.1. Ceramics. Ceramics are inorganic materials that have also been considered as replacements for bone grafts.

3.3.3.2.1.1. Hydroxyapatite. Hydroxyapatite (HA) can be developed in forms such as, powder, disk, block or granule; these are applied for skeletal treatments. HA is both biocompatible [60] and osteoconductive [61–63]. It has been available as a synthetic bone graft since the 1970s [64]. While HA exhibits good compressive strength, it is weak in tension and shear and susceptible to fracture on shock loading [64]. Hedge et al. [65] conducted a study of 31 elderly patients with unstable distal radius fractures who experienced closed reduction with K-wire fixation and synthetic HA augmentation (G. Surgiwear Ltd., Shahjanpur, India). Patient's fractures were reduced by means of traction-counter traction; in order to prevent loss of reduction they were then fixed with two crossed percutaneous K-wires, then HA bone granules were used to fill the fractures (Fig. 10) [65]. Suture removal and below-elbow cast application proceeded ten days following the procedure. The cast and K-wires were removed after four weeks; patients then began physiotherapy for the fractured wrist. Results at 16 weeks follow up showed that there were no incidences of metaphyseal defect or collapse and patients

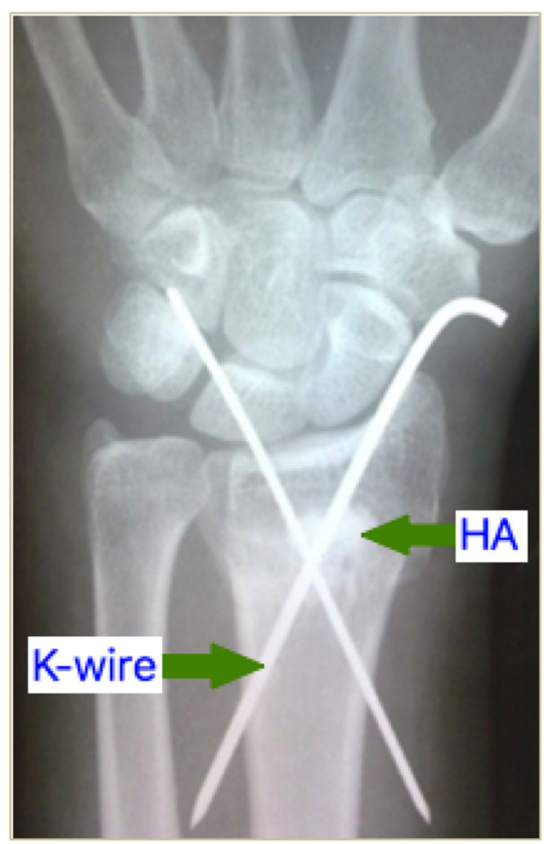


Fig. 10. Postoperative radiograph showing K-wire fixation and HA augmentation, adapted from [65].

showed improvements in regards to dorsiflexion, palmar flexion, ulnar deviation radial deviation, pronation and supination [65]. Complications included loosening of the K-wire ($n = 1$), a loss of reduction ($n = 1$), pin tract infection ($n = 3$), discharge (transparent, watery bodily fluid; $n = 1$) and shoulder hand syndrome (sever burning sensation, stiffness, swelling and discoloration of hand, arm, legs or feet; $n = 1$) [65,66]. Despite complications, the authors concluded that fixation with the augmentation of synthetic HA for treatment of unstable distal radius fractures in the elderly should be considered regularly [65]. Calcium Hydroxyapatite (CaHA) is osteoconductive, biocompatible and similar to mineralized bone [63,67,68]. Sakano et al. [69] performed external fixation on 25 patients with unstable distal radius fractures with CaHA. Results suggested there was a slight loss of radial height, however CaHA was a beneficial addition to external fixation for distal radius fractures and suitable replacement for bone grafts [69]. Another study was performed on elderly patients who underwent volar fixed angle plate for comminuted distal radius fractures with and without using CaHA [70]. Results suggested that no significant difference was detected between the two in regards to palmar tilt and radial inclination, although an increase in ulnar difference was shown within those patients treated with a volar fixed angle plate without bone graft in comparison to the patients who were augmented with CaHA [70]. The study suggested that a locking plate system would profit from the addition of CaHa substitute with regards to a comminuted intra-articular distal radius fracture [70].

3.3.3.2.1.2. Tricalcium phosphate. Tricalcium phosphate (TCP) has good biocompatibility and bioabsorability [71,72]. A randomized study was performed which consisted of 39 patients with unilaterial, intraarticular fractures of the distal radius. Patients were divided into two groups (those treated with internal fixation and those with TCP grafting) [73]. Both groups were treated with dorsal plate after corrective osteotomy [73]. It was indicated in regards to functional and radiographic results that there were no benefits with the use of TCP over internal fixation alone [73].

3.3.3.2.2. Injectable calcium phosphate cement. Calcium phosphate cements (CPCs) were discovered during the development of a re-mineralizing paste for dental caries [74]. The first CPCs were based on tetracalcium phosphate (TTCP) and dicalcium phosphate anhydrous (DCPA), which, when combined, transform into HA at neutral pH under isothermic conditions and at physiologic pH [75]. Due to this, CPCs are osteoconductive and osseointegrative [74,76] but exhibit long setting times and insufficient mechanical properties for most load bearing applications, particularly in tension and shear [74]. An *in-vitro* study investigated the stability of fracture fragments following fixation using CPCs with and without the use of supplemental K-wires; they also examined fracture fragments following alternative techniques of percutaneous fracture fixation [77]. The use of CPCs for unstable distal radius fractures have been considered with the hope of preventing stiffness resulting from extended periods of immobilization with casts or

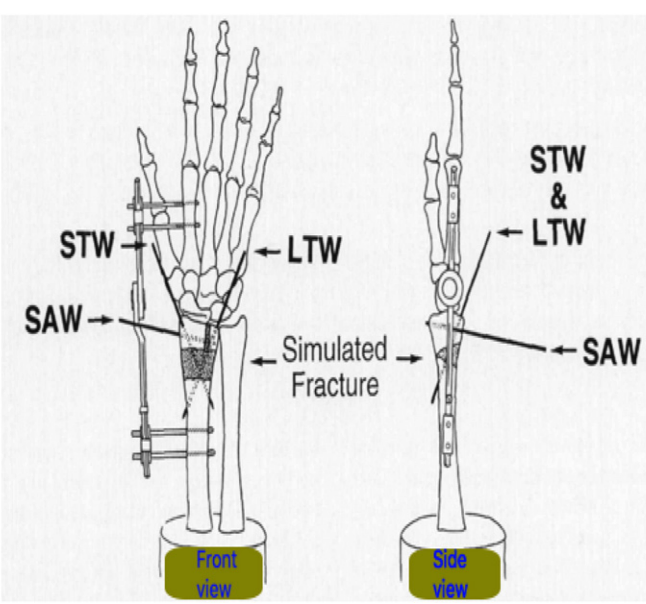


Fig. 11. Drawing of simulated intra-articular distal radius fracture procedure and augmented external fixation using a rigid external fixator, K-wire augmentation using radial styloid transfixation wire (STW), lunate facet transfixion wire (LTW) and subarticular wire (SAW), adapted from [77].

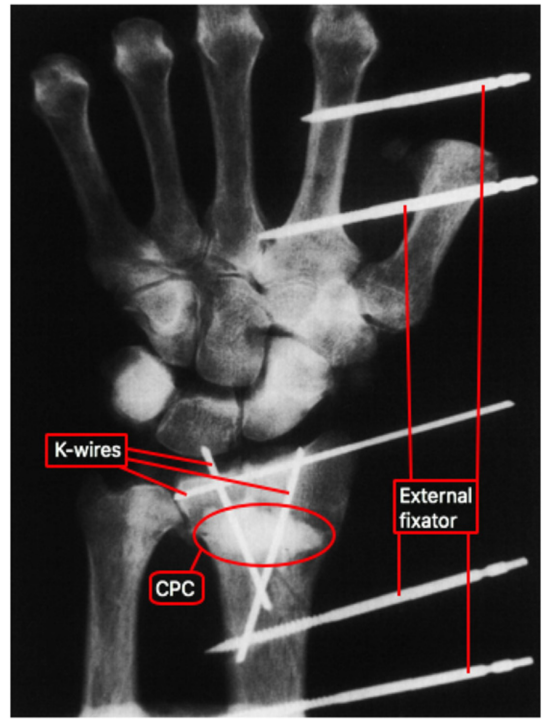


Fig. 12. Radiograph portraying simulated intra-articular distal radial fracture stabilized by CPC with three K-wires, (external fixator was used to accurately position the hand for radiograph imaging), adapted from [77].

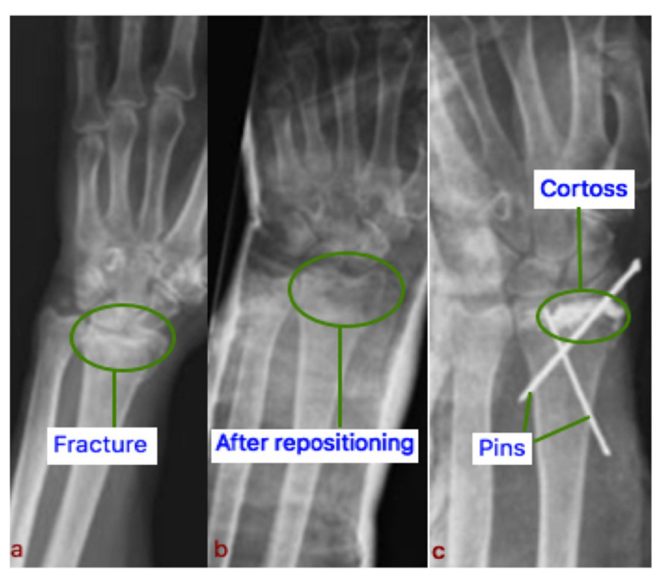
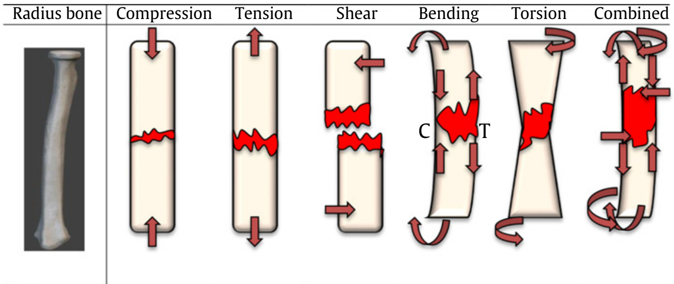


Fig. 13. a) Radiograph of the fractured left wrist, b) radiograph after repositioning and plaster cast immobilization, c) postoperative radiograph of the wrist with FFS® pins combined with Cortoss®, adapted from [81].

Table 1
Representation of various types of load applied to the radial bone (compression, tension, torsion, shear, bending or a combination.

Radius bone	Compression	Tension	Shear	Bending	Torsion	Combined



(Red): Fracture, → : Force Direction, For bending force *C: Compression and T: Tension*.

external fixation treatments [77]. The study consisted of seven fresh-frozen human cadaveric upper extremities that had randomly been placed into either an external fixation or cement group [77]. An intra-articular distal radial fracture with dorsal comminution and bone loss (Fig. 11) was simulated with a fracture model, while fractures for the other intact volar cortex were created by hand [77]. One wrist from each group was treated with an augmented external fixation device and three K-wires, while the opposite wrist was treated with CPC (Norian SRS; Norian, Cupertino, California) and three k-wires (supplemented CPC) (Fig. 12). Loads were then increased (up to 100 N), applied to the main flexors and extensors of the treated wrists [77]. Results indicated that fixation with CPC on its own had been unsuccessful in all samples examined at the bone-cement interface (<80 N) [77]. However, it was found that in four of the six axes examined augmented external fixation displayed a considerable increase in stability to the radial fracture in contrast with the stability of augmented CPC, which was found to offer better stability in three of the six axes than k-wires alone [77]. It was concluded that CPC on its own was not sufficient to endure the physiologic flexion-extension movements of the wrist. Supplemental wire fixation (K-wires) with the CPC allowed for more stability rather than K-wires alone, however the combination was found to offer considerably less stability than augmented external fixation [77]. The authors suggest that when CPC is used for treating unstable distal radial fractures then it is best to use supplemental fixation.

3.3.3.2.3. Injectable composites. Cortoss® (Orthovita, Malvern, USA) is a synthetic bone void filler that contains bis-glycidyl methylmethacrylate, bisphenol, trethylene glycol dimethylacrylate monomer, and bioactive glass [78]. Cortoss® is intended to imitate cortical bone. It is offered in a double lumen cartridge with uniquely designed tips used for mixing. Once the compound is expressed through these tips, polymerization initiates [78]. The elasticity of Cortoss® is similar to that of bone [79]. Despite the improvements Cortoss® offers, it still sets with an exotherm (63 °C) in excess of that associated with thermal necrosis of healthy bone tissue (56 °C) [80]. Smit et al. [81] reported the first case of a successful pin fixation of an unstable AO-A3 type distal radius fracture with Cortoss®. The patient was a 63-year-old woman with osteoporosis who suffered a fall and fractured her left wrist. Once the wrist was repositioned, X-rays still presented a dorsal angulation of 10° (Fig. 13a–b) [81]. Additional dorsal instability was anticipated and surgery was performed. The patient underwent an open reduction with fixation of two crossed FFS® (Fragment Fixation System) pins (Orthofix, Lewisville, TX), afterward Cortoss® was injected in the fracture (Fig. 13c) [81]. The patient's fracture was immobilized with plaster cast for two weeks [81]. Results found that during four weeks follow-up the patient presented good function of her wrist, during 11 months follow-up the patient had full functionality of her wrist, however the palmar flexion (71%) did not fully recover [81]. This did not interfere with her daily activities. The authors concluded that Cortoss® could be safely used for fractures of the distal radius. However, due to the relatively recent introduction of Cortoss® to the market and the subsequent lack of long-term stability studies, it is not currently possible to confirm the stability of this material over the longer term.

4. Mechanical testing (material properties and loading of bones)

Typically, the material properties of bone can be confirmed by performing mechanical testing, although at times ultrasonic testing is also performed. Mechanical testing involves applying tensile, compressive, torsional (torque), bending, shear loads, or a combination to bone samples (Table 1) followed by documenting the deformation of the material that has been used [82]. It is only following this procedure that the structural properties (force-deformation) or material properties (stress-strain) curves are confirmed [82]. Unfortunately, it can be difficult to perform mechanical testing on bone as it involves testing several samples and small sample sizes can make it challenging.

4.1. Mechanical testing for wrist fractures

Klitscher et al. [83] conducted a study which compared the biomechanical stability of the Dorsal Nail Plate (DNP; Hand Innovations, LLC, Miami, FL), a dorsal locked hybrid of nail and plate, and the XSCREW (Zimmer, Freiburg, Germany), an implant that uses both cannulated screw and K-wires, in fixation of a cadaver bone model of a distal radius fracture. The study consisted of three male and five female fresh-frozen

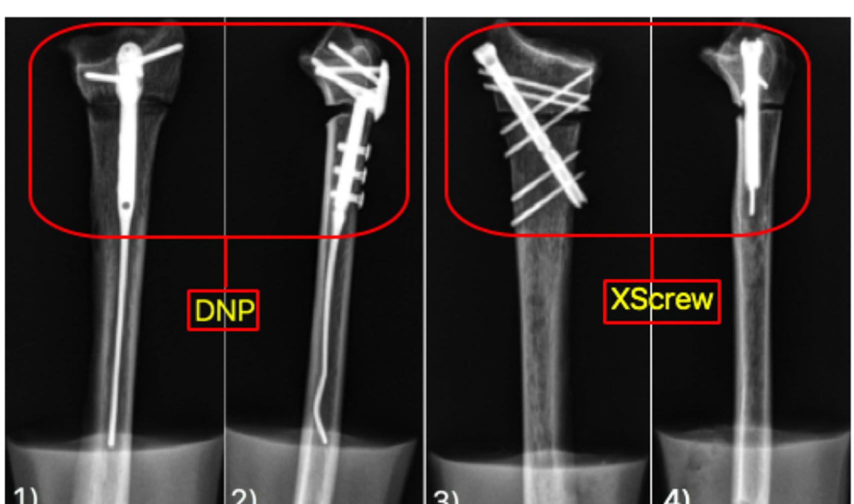


Fig. 14. Postoperative radiographs with implant fixation prior to biomechanical testing. 1–2) After fixation with a DNP. 3–4) After fixation with an XSCREW, adapted from [83].

cadaver radii, which were stored at −25 °C until testing [83]. Preparation of the radii included each radii being cut at 13 cm proximal to the articular surface, then the radius shaft as well as the distal end were firmly placed in methyl methacrylate [83]. Each radial sample was tested intact with a servo-pneumatic materials testing machine (Sinco Tec, Clausthal-Zellerfeld, Germany) [83]. In order to stimulate an extra-articular surface, the researchers performed a volar open wedge osteotomy using an oscillating saw with a kerf (the width and thickness of a cut made by the saw blade) size of 2 mm, in turn creating a 5 mm volar gap and a 2 mm dorsal gap [83]. When it was time to apply the implants, the researchers followed the appropriate application as suggested by the manufacturer [84,85]. Randomized pairs allowed for the equal application of each implant to be four times in the right radius and four times in the left radius [83]. Before any biomechanical tests commenced, researchers confirmed proper implantation through radiographs (Fig. 14).

Biomechanical testing first consisted of 6 cycles of axial loads of 10 to100 N and torque loads of −1.5 to 1. 5 Nm with sinusoidal load alterations applied to the intact radius [83]. Once DNP or XSCREW were implanted, the same six cycles took place again following the same application procedure. Following this, 1000 cycles of dynamic torque load alterations were carried out of 0.5 to 1.5 Nm at 0.5 Hz of 10 N [83]. After 1000 cycles, each sample that was still intact resumed loading in torque until failure. Fig. 15 displays an XSCREW-fixed sample positioned in the testing machine [83].

Results showed the axial stiffness of XSCREW-fixed specimens (median of 136.0 N/mm) were not statistically different to DNP-fixed specimens (median of 69.5 N/mm) [83]. The torque stiffness of XSCREW-fixed specimens (median of 0.163 Nm/°) was found to be significantly higher compared to DNP-fixed specimens (median of 0.068 Nm/°) [83]. The XSCREW-group presented axial stiffness of 33% and the torque stiffness of the intact radii was 49%, while the DNP-group presented axial stiffness of 14% and the torque stiffness of the intact radii was 20% [83]. Throughout the 1000 cycles of dynamic torque load alterations, failure did not occur in four samples in the XSCREW group and one sample of the DNP group, however cyclic loading resumed until failure [83]. Failure occurred by longitudinal fracture in the sagittal plane along the monocortical screws of the proximal fragment in five cases within the DNP group (Fig. 16), the osteotomy gap was found to have partial or complete closure in three of these five cases; in two cases there was no closure of the osteotomy gap, unfortunately in one case the DNP broke out and there was closure of the osteotomy gap [83]. Failure due to irreversible deformation of the implant-bone construct in the

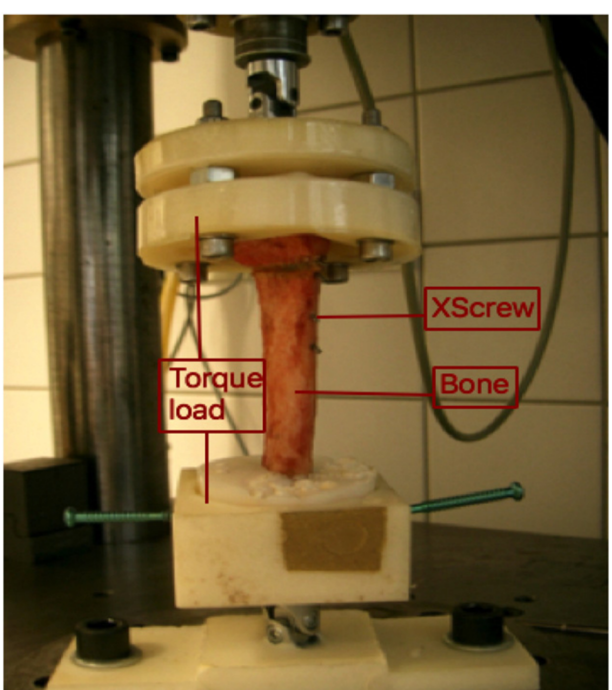


Fig. 15. XSCREW-fixed sample in the testing machine, adapted from [83].

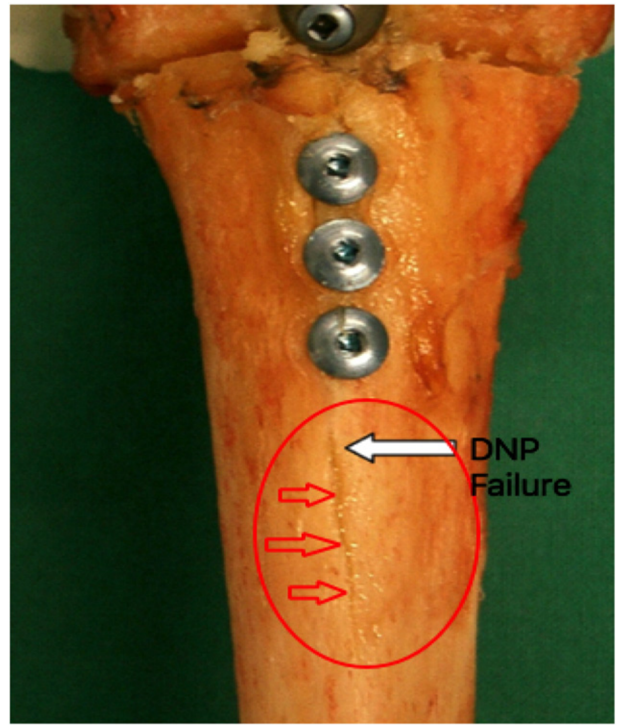


Fig. 16. DNP-fixed sample following failure (white and red arrows), adapted from [83].

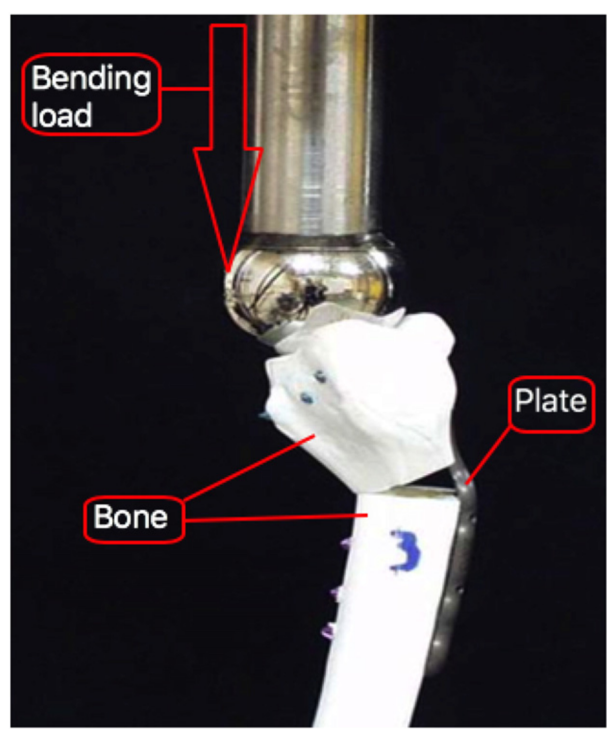


Fig. 17. Resulting load to failure. Sphere proceeded until failure or the dorsal edges of the fracture touched, adapted from [86].

distal was shown in two cases, resulting in the osteotomy gap being partially or completely closed [83]. The XSCREW group exhibited three cases that resulted in the screw breaking out of the distal fragment, with closure of the osteotomy gap [83]. In two of these cases, there was no closure in the osteotomy gap while another case had partial closure, although failure was found in one case due to the irreversible deformation of the implant-bone construct in the distal fragment [83].

The researchers suggest that stability and micro-motion at the fracture site are important in order for the fracture to heal [83]. It is also suggested that in order to successfully determine if novel devices are suitable alternatives for fixation of distal radius fractures, more clinical studies with longer follow ups and additional biomechanical studies using various fracture types are required [83].

Sobky et al. [86] compared the biomechanical properties of four volar fixed-angle fracture fixation plate designs in a new sawbone model as well as in cadaver bones. Researchers used left sawbone radii with white plastic cortical shell and foam cancellous core (#1105, Pacific Research Labs, Vashon WA) [86]. A 10 mm gap was created with a saw starting 20 mm proximal to the articular surface at Lister's tubercle in order to stimulate the fracture [86]. The incisions were created perpendicular to the long axis of the bone causing a consistent fracture gap on the dorsal and volar sides of the radius [86]. Four volar fixed angle-plating systems were examined in this study; a Hand Innovations double row DVR-A plate (Hand Innovations, Miami, FL), Avanta SCS/V (San Diego, *CA*), Wright Medical Lo-Con VLS plate (Arlington, TN) and Synthes volar radius stainless locking plate (West Chester, PA) [86]. Plates taken from each fixation system were inserted in sawbones (#1105, Pacific Research Labs, Vashon, WA). The synthetic radius models were preserved in metha methacrylate and an Instron (Instron corporation, Canton MA) bi-axial servo-hydraulic test frame (model 1321) was used for mechanical evaluation [86].

A cobalt chrome sphere was centered over the articular surface and advanced at a steady rate of displacement of 10 mm/min; load to failure was tested in six plate radii constructs of each group of samples [86]. The sphere proceeded until failure or until the dorsal edges touched (Fig. 17).

In order to compare sawbones to human cadaveric bone, researchers implanted two of each plating system into fresh-frozen cadaver radii [86]. Load to failure was performed in the eight samples in order to examine probable variances in mode of failure and the force necessary for bending the construct [86]. It was concluded that failure occurred in plates in all four groups. It was also shown that the DVR plate presented a considerably higher load to failure after fatigue cycles compared to any other plates [86]. ANOVA single factor data analysis showed that the DVR plate had the highest stiffness in single load to failure (162 N/mm), however it was not significantly stiffer than the other plates [86]. The analysis verified there was no plate breakages found in any of the groups [86]. The cadaveric bone presented a similar mode of failure as the sawbones [86]. No plate or screw breakage under loading occurred and there was no pull out of proximal or distal fixation [86]. Sobky et al. [86] concluded that each plate included in their study is able to endure physiologic loading in order to permit early wrist ROM following surgery for distal radius fracture.

Table 2
Summary of the most commonly used treatments and procedures for fractures of the distal radius and scaphoid.

Type of treatment	Advantages	Disadvantages
Cast/splint	• No exposure to risks associated with surgery • If able, quick return to work and daily activities	* Immobilization up to 6 weeks * Restrictions of some daily tasks
Internal fixation	• Increase in stability • Precise placement of the implant • No need for external devices • No interference of casts • Possibly a faster healing time	* Stiffness * Infection * Nerve injury * Potential for nonunion * Tendon inflammation * Loss of reduction with fracture collapse * Carpal tunnel syndrome (CTS)
External fixation	• Minimum disruption of soft tissue • Temporary hardware • Minimal scarring after the incision	* Infection * Delayed union
Percutaneous fixation	• Stability for closed reduction • No requirements for permanent hardware • Minimal soft tissue complications • Reduced pain from surgery • No surgical incision	* Infection * Pin loosening * Malunion
Reduction	• Quick recovery • Less risk for infection	* Reoccurrence is possible
Bone grafts	• Provides stability • No loss of reduction	* pain in the donor site * Swelling or blood clots in tissues * Infection * Morbidity * Cost
Injectable CPCs	• Biocompatible • Osteoconductive • Osseointegrative	* Cannot endure physiologic flexion--extension movements of the wrist on its own * Requires the use of supplemental wire fixation to allow for more stability
Cortoss®	• High strength	* Exothermic reaction causing thermal necrosis of healthy bone tissue

5. Conclusion

Table 2 presents the advantages and disadvantages of the most common treatments and procedures used for fractures of the distal radius and scaphoid.

Minimally invasive surgery can be used for treating fractures of the distal radius and scaphoid. There are many treatments and procedures used to treat both types of fractures, however there are risks associated that affect patient outcomes. Newer treatments and procedures such as injectable CPCs have potential, however CPCs alone provide insufficient stability to withstand physiologic flexion-extension motion of the wrist, due to their poor strength under tensile and shear loading. Recent procedures include applying injectable cements such as Cortoss® that are reported to offer sufficient strength and bonding to aid in the rapid healing and reconstruction of the fractured bone.

Acknowledgement

The authors gratefully acknowledge the financial assistance of the Collaborative Health Research Project, CIHR/NSERC (315694-DAN).

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