Preliminary Considerations on Non-invasive Home-Based Bone Fracture Healing Monitoring

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Abstract. Fractures are common injuries causing pain and morbidity. Stable fractures with acceptable initial alignment are treated by immobilization. The alignment and angulation need to be controlled during the first 1–3 weeks (depending on the fracture), because the alignment may worsen. This is performed by taking X-ray images of the fracture site. Repetitive X-rays expose the patient to ionizing radiation repetitively. We have studied techniques to monitor the alignment of the fracture continuously and without the routinely taken control X-rays. The idea is to place sensors underneath the cast and on to the skin of the patient that would follow the angulation and alignment of the fracture and alert if a change is detected. Two approaches with radio technology are made: transmitter-receiver pairs and radar pairs. The challenges and their possible solutions are discussed.

Keywords: cast · children · UWB · radio technology · transmitter · receiver · radar

1 Introduction

Bone fractures are such common injuries that they are considered as a public health issue in global scale [1]. According to [1] the age-standardized incidence rate of fracture globally was 2296.2/100 000 in 2019. The fracture of hand, wrist or other distal part of arm are the most common sites of the fracture: Wu et.al. State that the age-standardized incidence ratio of these fractures in 2019 was 175.9/100 000 [1].

Fractures cause pain and morbidity to children as well. Literature implies that 27%-50% of children suffer at least one fracture before the age of 18 [2, 3]. The incidence of childhood fractures before the age of five has been shown to be 50–100/10 000 person years in European population [4–6].

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Distal radius fracture is a very common wrist injury, which is usually caused by a low-energy injury [7]. The usual mechanism of injury is falling on an outstretched arm from a standing height. The risk of suffering of a distal radius fracture is highest among post-menopausal women and adolescent males [7].

The most common method of treatment for any stable fracture is closed reduction (if needed) and immobilization in a cast. This is the accepted treatment also for stable distal radius fractures. A fracture is considered stable when the alignment of the bone is acceptable after reduction and the possibility of displacement is considered small [8]. Surgical treatment is considered if the proper alignment cannot be accomplished by closed reduction, the alignment fails in control x-rays taken at 1–2 weeks after injury or the features of the fracture predict poor functional outcome of the wrist.

Although, immobilization by casting is applied, the alignment of the fracture can still change into worse before the fractured bone is ossified. Typically, the alignment of the fracture is monitored by taking a control X-rays during the first weeks after the trauma. This exposes the patient to ionizing radiation on several occasions, which may have cumulative consequences (i.e., an increased cancer risk). The risk is higher among children due to their smaller size and immature tissue composition. Further, clinical and radiographic follow-ups have economic effects on the patient/family and the society as they require visits to the healthcare. Therefore, our research group is developing a method to monitor continuously the angulation and displacement of the fracture by sensors that are attached either directly to the skin or percutaneously to the bone by using extremely thin pins. These sensors will remain beneath the cast. The approach discussed in this paper utilizes radio-based sensors with sophisticated wireless communications solutions to measure and transfer constantly their reciprocal orientation using radio waves and alert if the distance or angle between them change. By using this method, it would be possible to monitor the position of the fracture constantly and thus avoid the regular control X-rays. The proposed monitoring can be done non-invasively. The system will alert if it detects significant change in the fracture alignment and then the patient will contact healthcare for a control X-ray. Based on our current knowledge, there are no existing radio-based displacement monitoring systems available for clinical use. In the first phase, we will concentrate on distal radius (i.e., wrist) fractures, because they are very common and there is no extensive amount of soft tissue surrounding the radius and ulna.

2 Anatomy of the Forearm

The bony structure of the forearm is formed by radius and ulna. They are connected distally by the Distal Radio Ulnar Joint (DRUJ) and proximally by the Proximal Radio Ulnar Joint (PRUJ). These joints enable the pronation-supination-movement of the forearm. In addition, the radius and ulna form a joint with the carpal bones enabling the flexion and extension of the wrist, as well as adduction and abduction. The distal radial articular surface is tilted in the volar direction 11° in average (variation 2°–20°) and the mean inclination angle is 22° (21°–25°) [9], see Fig. 1. Ulna is approximately 0.5 cm shorter than radius at the DRUJ, but there is large variation individually (1–5 mm).

The long bones can be divided into three distinct regions that are important to separate, especially in children: diaphysis, metaphysis and epiphysis. The diaphysis is the hollow shaft of a long bone, the epiphysis is the round and wide end of a long bone, the metaphysis resides between the epiphysis and diaphysis, and it is separated from the epiphysis by the growth plate during childhood (see Fig. 2). The longitudinal growth of a long bone happens mainly in the metaphysis and therefore the bone tissue is softer in this region. Thus, the pediatric bone fractures are most often located in the metaphysis.

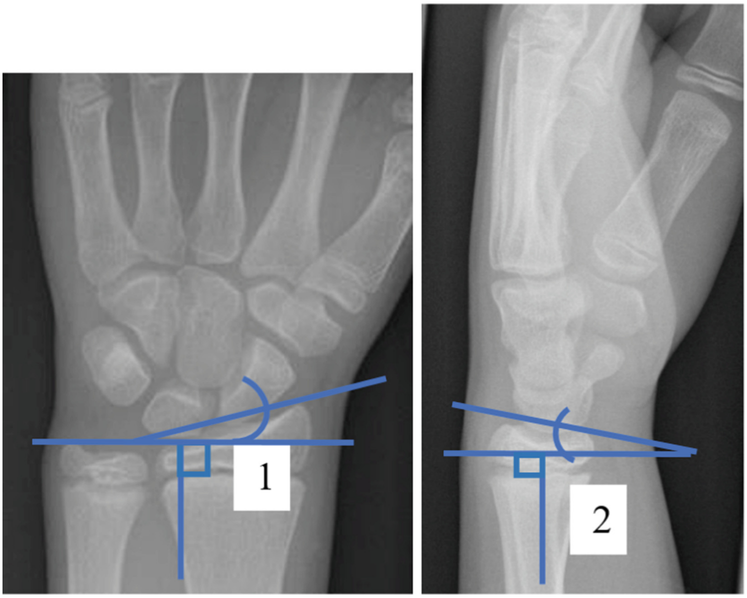

Fig. 1. The anatomy of the radius: 1) inclination, 2) volar tilt. Picture by Dr Ian Bickle, Radiopaedia.org, Creative Commons License, https://creativecommons.org/licenses/by-nc-sa/3.0/.

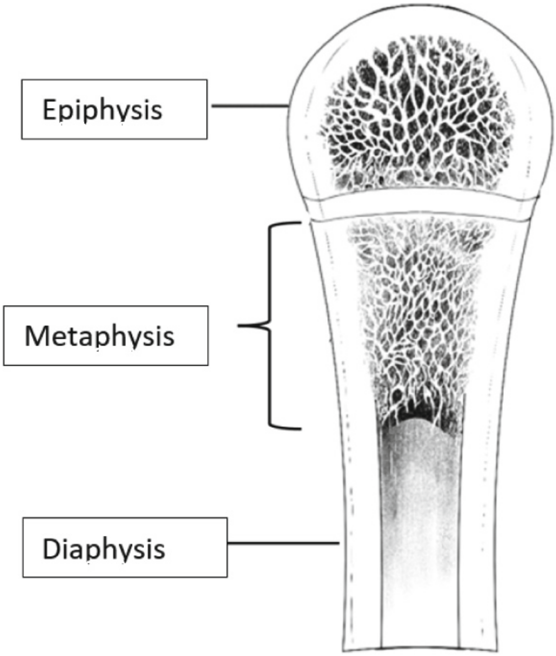

Fig. 2. The regions of a long bone. Picture modified from Parviainen, R. "The intrauterine and genetic factors associated with the childhood fracture risk", Acta Universitatis Ouluensis, D1591, 2020.

3 Fractures and the Treatment

The types of fractures can be divided roughly to stable torus fractures, bowing fractures, greenstick fractures (these three types happen only in children), transverse fractures with exact alignment and transverse fractures with varying degree of displacement and angulation. An example of a distal radius fracture with dorsal angulation is depicted in Fig. 3.

If the alignment and angulation of the fractures is acceptable the fracture can be treated by casting. The material used in the cast is either traditional calcium sulphate or fiberglass. When the fracture is immobilized using a cast, the alignment of the fracture must be controlled in the first 1–2 weeks by X-rays. During this period, the ossification of the fracture has just begun and the angulation or the displacement may worsen. The most important parameter that is followed in distal radius fracture is the dorsal of volar tilt seen in the lateral X-ray. In adults, the acceptable angulation is 15–20 degrees dorsally and under 20 degrees in the volar direction. In children, the acceptable angulation in the primary situation can be greater (20–30 degrees) depending on the age [10].

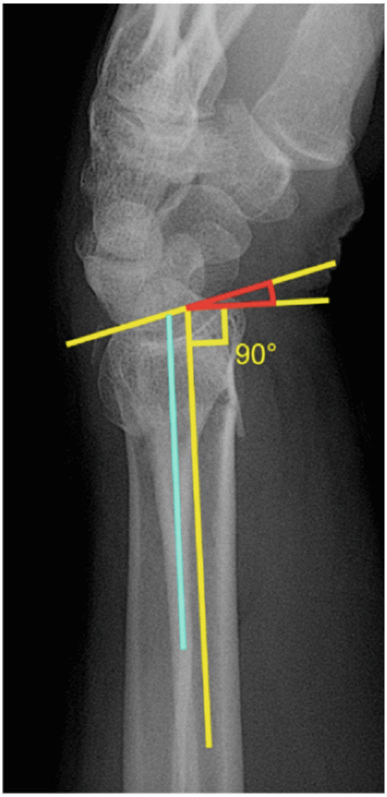

Fig. 3. Typical radius fractures with dorsal tilt. Picture by Mikael Häggström, Creative Commons License, https://creativecommons.org/licenses/by-sa/3.0/deed.en.

4 Example of the Needed Measurement Accuracy

In distal radius fractures 5–10-degree change compared to the starting point may be meaningful. If the width of the radius is 2 cm (in anterior-posterior dimension), it would mean that 5–10-degree change in the angulation would result in 17–35 mm change in vertical direction measured at the edge of the bone (see Fig. 4A). The younger the person with the fracture is, the smaller the bones are. Therefore, the vertical change may be smaller. The horizontal change is affected more by the location of the fracture (see Fig. 4B). From these calculations it is evident that the distances and angles that need to be measured are quite small. This places high demands on the accuracy of the monitoring system, especially as the system is planned to be placed on the skin. The skin sensor placing must be carefully considered and it is dependent on the type and location of the fracture. The sensors should be placed in such a way that there is as small amount of soft tissue as possible between the sensor and the bone.

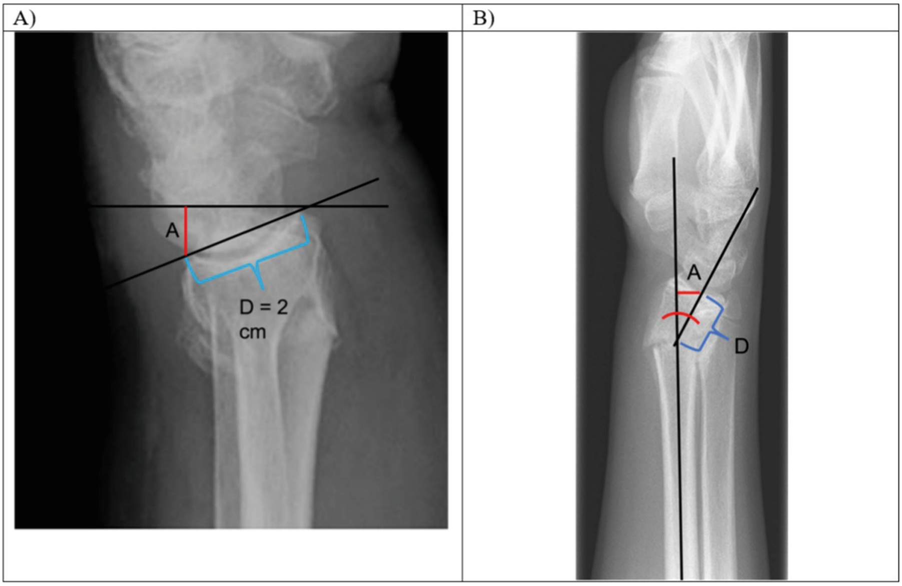

Fig. 4. A) Example of the amount of vertical displacement if the width of the bone is 2 cm and the dorsal tilt caused by the fracture is 10 degrees. The length A is 3.47 mm. B) Example of the amount of horizontal displacement if the fracture location is 3 cm (D = 3 cm) from the head of the bone and the dorsal tilt is 20 degrees. The length A is 1.02 cm. Picture by Roope Parviainen ©.

5 Possibilities and Challenges from Radio Technological Point of View

The scope of this work is to consider possible solutions for monitoring the bone fracture healing process at home and on a continuous basis during the whole healing process in an non-invasive manner. In the literature, there are corresponding solutions, which are using invasive methods [11, 12] requiring surgical operations. Non-invasive methods are proposed, e.g., in [13, 14] based on radio waves by measuring scattering parameters. They may however need quite sizeable measurement devices or are more suitable to detect the presence and size of a fracture instead of the healing process itself.

Two possible radio-based approaches are presented to detect an abnormal healing of a fracture. Besides being non-invasive, the solutions should be as small and light as possible, very reliable and dependable, easy to install and easy to monitor the results by the user, inexpensive, comfortable to wear during the healing process and have low power consumption. Furthermore, as described in Fig. 4, the accuracy or resolution demand for the solution is very high, up to less than 5 mm in distance, or 10 degrees in angle.

5.1 Several Transmitter/Receiver Pairs

The first approach to present is the usage of several transmitter (TX) and receiver (RX) pairs. The concept is depicted in Fig. 5. TX and RX are mounted under the cast directly on the skin of the patient on both sides of the bone fracture. For simplicity the skin is not drawn. Time of flight of the signal can be measured and based on the result the distance can be found out. On the right side of Fig. 5 the situation of an abnormal fracture healing process is illustrated. The bending of the bone causes a change in distance between the TX/RX pair indicating the need for more detailed examination carried out by a doctor. Since the bone may bend in different directions, several TX/RX pairs are needed.

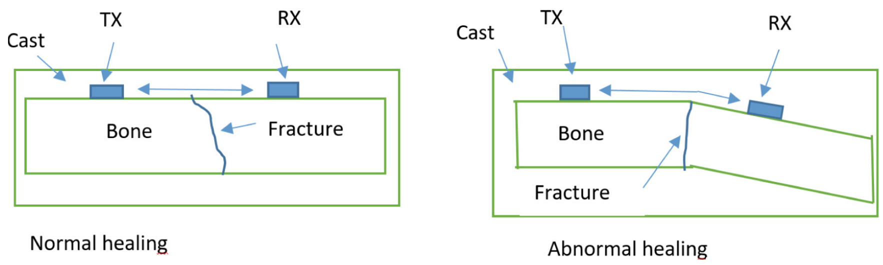

Fig. 5. TX/RX approach.

One serious challenge in this method is the demand of high resolution in distance. It is well known that the time resolution is the inverse of the signal bandwidth [15, 16]. Assuming the speed of light *c* in air this will lead to a distance resolution *R* stated as

$$R = c/B, \tag{1}$$

where *B* is the signal bandwidth. It is obvious that for a high distance resolution a wideband signal is needed. One technique possessing a wide bandwidth is impulse radio ultra wideband (IR-UWB) technology [15, 16].

However, assuming, e.g., a target resolution of 5 mm for the concept it would correspond approximately the need of a signal bandwidth of 60 GHz. This is impossible to accomplish in practice not only due to the bandwidths of the existing antennas but also due to the nonexistence of pulse generators to be able to produce such a short pulse in time, 0.17 ps.

By using advanced signal processing methods, the signal bandwidth demands could be relieved. In [17, 18], interpolation method is proposed. Based on the results, in theory, e.g., 1 mm resolution could be achieved with a bandwidth of approx. 10 GHz. The method assumes a correlation receiver structure. Furthermore, in [19] a pulse generator in presented being able to produce a pulse of approx. 120 ps in time, corresponding roughly 8 GHz in bandwidth.

Instead of using IR-UWB time of flight approach also the usage of received signal strength indication (RSSI) was considered. However, with RSSI the resolution problem may be seen from a different angle: since the resolution demand in distance is high, the power decay in just a few millimeters of a distance difference may be impossible to detect.

5.2 Radar Approach

The second approach considered is the use of radars. The concept is presented in Fig. 6. A radar pair is installed on or in the cast on both sides of the bone fracture as depicted. Radars are sensing the distance to the bone on both sides. At the installation phase the distances are recorded as a reference on both sides, as shown in the normal healing case. Should abnormal healing occur on either side of the fracture the distance changes leading to an alert due to the bending of the bone. At minimum two pairs of radars would be needed to monitor the possible changes in different directions.

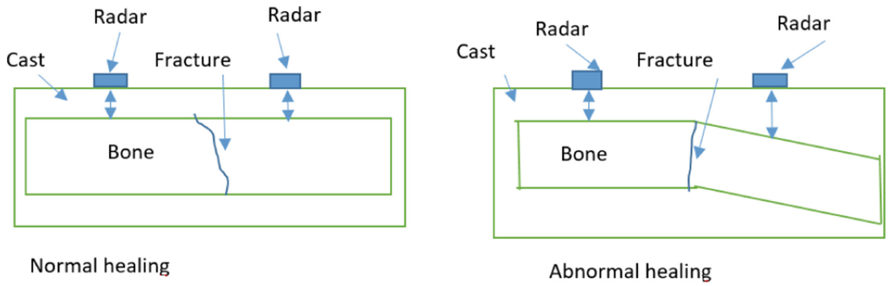

Fig. 6. Radar approach.

As with TX/RX approach in Sect. 5.1, one of the key questions in the radar approach is the distance resolution. Similar kind of methods as in [17, 18] could be applied here as well, assuming UWB communications in time domain. Regarding to signal processing methods, in [20, 21] also other signal processing methods are proposed for an UWB radar to increase accuracy. However, even though they are presented to be used as monitoring vital signals of a human, such as respiratory rate and heartbeat, they are not suggested to be used for bone fracture monitoring or to be used at the extreme vicinity of a human body, i.e., on-body.

Considering the concept in Fig. 6, another challenge can be noted. As the radars are thought to be on the cast or in it, the distance to be defined by the radars will be short, perhaps only 2–3 cm. Assuming pessimistic propagation speed of the signal in air, the echo will start to return already after approx. 0.02 ps. If the pulse generator operates as in [19] (pulse duration 120 ps), normal pulse radar does not have time to turn into the reception mode.

One solution to this could be to use full-duplex type of receivers [22] with pulse radars. Another solution could be to use a frequency modulated continuous wave (FMCW) radar where the previous mentioned problem does not, in theory, occur. FMCW radars are investigated, e.g., in [20, 21] at 77 GHz center frequency area but the minimum measurement distance is noted to be on the level of 3.5 cm.

Finally, in theory with radar approach, several echoes will arrive to reception from skin, fat, muscle and bone as noted in [23].

6 Conclusion and Future Work

This paper presents preliminary considerations leading to two possible approahes on non-invasive bone fracture healing monitoring. The monitoring is planned to be conducted at home continuously. The background on bone fractures and their healing, as well as the rationale for this approach is given. Furthermore, detailed exemplary cases from real life showing the demands for the question under scope are given.

The resolution demands are high, as the distances are very short. In here, our team discusses on two different approaches based on radio signals. Firstly the use of several transmitter-receiver-pairs by using either time of flight technique or RSSI measurement. In this case, the resolution can be seen as the main problem. Possible solutions related to digital signal processing are proposed to ease up the problem.

The second presented approach is based on radars at short distance. Also here, the resolution problem is present, even though similar kind of solutions as with transmitter-receiver pairs could be applied. However, in this case very short distance to be measured by radars sets limits to the technology to be used.

As future work, the two presented approaches should be examined in more detail also beyond theoretical investigations. Furthermore, other technologies outside the scope of the presented ones in this paper will be under research.

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