3D imaging in corrective osteotomy of the distal radius

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SUMMARY AND CONCLUSIONS

When somebody falls on the outstretched hand (a so called FOOSH) the most common fracture is of the distal radius, one of the two forearm bones. A distal radius fracture is usually treated conservatively with a plaster cast. Sometimes the two parts of the broken radius unite in a wrong position. This is called a malunion of the radius. In such a case the radius is often shortened and the angulation is reduced, and there may also be a rotation of the bone around the bone axis. If the patient has symptoms (limitation of motion, strength reduction and/or pain) due to the wrong position of the bone, we call it a symptomatic malunion. The incidence of a symptomatic malunion is estimated at about 5% of all wrist fractures every year. This thesis deals with the treatment of malunions of the distal radius.

The surgical treatment is a corrective osteotomy, a procedure to restore the original anatomy of the distal radius. Osteotomy literally means “cutting through bone” and with a corrective osteotomy of the radius the bone is completely cut, preferably at the level of the original radius fracture. Subsequently the two bone segments are placed in a correct relative position to each other. This improved position is often supported by a piece of bone from the hip of the patient (the iliac crest), plus a fixation plate and screws to fixate the bones in the new position.

Due to the complex anatomy of the wrist, and the fact that besides shortening and reduced angulation of the bone, often a rotational deviation around the bone axis is present, planning of a corrective osteotomy is often technically difficult. A malunion comprises a “3D” deformation and repositioning needs to be addressed in six degrees of freedom. Conventional methods use 2D imaging (X-rays) for planning and evaluation of the corrective osteotomy. However, these planning and evaluation methods have limitations, as is examined and described in this thesis. Also, the conventional method of bone fixation with plate and screw fixation is invasive.

The research described in this thesis is on the development, design, implementation and testing of new techniques for corrective osteotomy of the distal radius. The goal of this thesis is threefold. At first, possible pitfalls of conventional corrective osteotomy surgery were determined and quantified (Part I). In addition, 3D planning methods (Part II) and new surgical techniques (Part III) were investigated that assist the surgeon in restoring the anatomy of the wrist more accurately.

Part I - Conventional 2D practice

Chapter 2 presented an overview of long-term follow-up surgery data in the region of Amsterdam for the conventional corrective osteotomy procedure of the radius. This inventory of hardware removal and re-operation rates can later be useful as reference data in comparing new and improved techniques with the conventional technique. The study showed that the conventional 2D procedure of the corrective osteotomy of the
radius has limitations and can give problems over the long term. The re-operation rate and number of hardware removals that we found in this retrospective study is higher than previously described in short-term follow-up studies. The average duration of our follow-up is 37 months (range 6-66). The total re-operation rate is 38%. Nine percent of all patients underwent either a re-corrective osteotomy of the radius or an additional ulna shortening osteotomy. The other 29% of the patients needed a re-operation for hardware removal. The high rate of hardware removals may indicate a need for other - less invasive - fixation methods in a corrective osteotomy of the distal radius. Only 3% of the patients had other non-hardware related complications, which makes the procedure relatively safe. Since this study was only an inventory of re-operation rates and did not investigate the clinical outcome of the conventional corrective osteotomy procedure, we presented a retrospective study in Chapter 3. The aim of this study was to investigate the residual malposition of the distal radius after conventional surgery. Twenty-five patients who underwent a conventional corrective osteotomy of the distal radius based on 2D planning were included. The results showed that 2D planning and the use of conventional fixation hardware do not yield optimal repositioning. 3D image based evaluation was used and we found considerable residual errors in the post-operative position compared to the unaffected contralateral radius, which is considered as a good reference in the literature. This confirmed suboptimal repositioning. Moreover, statistically significant correlations were found between the 3D rotational deficits and clinical outcome. These correlations were not found with 2D evaluation parameters. This can be explained by the extra dimensions seen with 3D imaging, which are missed on 2D radiographs due to overprojection. Considerable residual malalignments and the statistically significant correlations between malalignment parameters and clinical outcome confirm the need for better techniques. Deficits in all 6 degrees of freedom that are unseen on 2D images have to be restored, using 3D planning and surgical techniques for better positioning in 3D space.

Another challenge in conventional corrective osteotomy procedures is the fixation method. Chapter 4 examined the accuracy of standard anatomical fixation plates for positioning a distal radius fracture, using two different types of plates. Anatomical plates are supposed to bring the radius in its original position. We hypothesized that positioning is influenced by the differences in morphology between radii, different plate shapes and subjective placement of the plate by the physician. For this experimental explorative study we used radii made of acrylonitrile butadiene styrene (ABS) in a 3D printing machine, based on CT scans of healthy subjects. We found a considerable number of cases in which the residual errors of the positioning were large. We concluded that positioning with an anatomical plate may lead to considerable rotational deviations for individual cases, mainly due to plate placement by the surgeon. These 3D rotational deficits are exactly the parameters which have a statistically significant correlation with clinical outcome (Chapter 3). Anatomical distal radius plate shapes appeared to be different among plate manufacturers. One plate
may therefore perform better than the other for an individual patient. In addition, when
the bone geometry is deformed, for example in a malunited radius, an anatomical plate
is unlikely to provide optimal positioning since the anatomical plate is designed for the
undeformed bone anatomy.

Part II - Towards 3D planning

Chapter 5 gave an overview of proposed methods to perform a corrective osteotomy
with the help of 3D imaging. It showed that 3D pre-operative planning is only part of
the solution. Without a method of guiding the surgeon, there is no guarantee that the
planned results will actually be accomplished during surgery. The review demonstrated that
many existing 3D preoperative planning systems for osteotomies do not include a guiding
system and when they do, it is an invasive method with mechanically adjustable complex
navigation systems. The review concluded that it is necessary to search for new methods
that enable accurate positioning in 3D space, preferably using less or minimally invasive
surgical techniques.

In the literature review described in Chapter 5 the contralateral side is generally accepted
as the best reference for restoring the affected side. However, the assumption of perfect
bilateral symmetry between the left and right forearm bones was never investigated in 3D.
Therefore, we evaluated in Chapter 6 the bilateral symmetry of the long forearm bones
with the help of 3D imaging. We found an asymmetry between intra-individual radii and
intra-individual ulnae. Especially bone lengths were found to be different between both
arms. This natural asymmetry in the forearm confirms that surgical planning using the unaf-
fected side may not be as useful as previously assumed. Fortunately, a clear correlation was
found between length differences of radii and ulnae. The ulna length difference is a good
parameter for compensating the radius length difference, and vice versa. We recommend
to use this relationship during preoperative planning of a corrective osteotomy to correct
for length errors in the position that exist due to natural occurring bilateral asymmetry. In
Chapter 7 we presented a method that includes the bilateral length relationships of both
forearm bones into the preoperative planning. We tested this solution on twenty healthy
individuals by simulating a corrective osteotomy procedure. We also virtually tested the
method on patient data. By including the length difference of the ulnae in our planning,
we found that this gives better positioning results than planning without taking the ulnar
length into consideration. This confirms our hypothesis formed in Chapter 6. By correcting
the radius length with the length difference between the two ulnae during planning, the
length error was reduced by a factor two compared to planning without length correction.

Part III - New 3D techniques

In Chapter 8 we described a patient-tailored plate. This is a plate designed to overcome
the errors that would be introduced using a standard anatomical plate in the fixation of
a corrective osteotomy of the radius (Chapter 4). This individually made plate only fits in one way on the patients bone geometry and realigns the bone segments as planned. This method uses pre-operative 3D imaging to plan positioning of the segments of the radius and to design the plate. The method is evaluated using artificial bones and proved to be highly accurate and very reproducible ($d_{err} < 1.2 \pm 0.8 \text{mm}$ and $\varphi_{err} < 1.8 \pm 2.1^\circ$). The patient-tailored plate is expected to be of great value for future corrective osteotomy surgery in complex cases.

To introduce a technique that has potential to be minimally invasive, we also developed an alternative method described in Chapter 9. This chapter introduced a new technique that uses pre-operative 3D planning in combination with intra-operative 3D imaging. After inserting pins with marker tools in the proximal and distal part of the radius before the osteotomy takes place, it is possible to match the intraoperative situation with the pre-operative plan, which allows calculating parameters for repositioning the bone segments using the inserted pins. Positioning tools were developed (the manipulator fixator system) to correct the distal radius position in six degrees of freedom by navigating the pins. Small incisions for pin placement and for the osteotomy render the method minimally invasive. The cadaver experiment in this study proved our proposed minimally invasive method to be accurate and highly reproducible.

The major advantages of the proposed methods are the ease of applicability in the operating room with objective placement and the improved accuracy of repositioning and evaluation using all six degrees of freedom. Specific benefits of preoperative virtual planning include the ability to perform multiple simulations of the surgical procedure, which can be used to optimize the plan and identify potential problems during realignment. The planning tool can also be used to teach residents through visualizations of the deformity and by simulating different ways of correcting the malunion.

**Future perspectives**

The issue of a possible absence of a healthy contralateral radius still needs to be addressed. A solution would be to create a statistical shape model of the radius. In planning based on a statistical model, relationships between the different bones in the wrist could be calculated and analyzed without the need of an extra CT scan of the contralateral wrist. Future research should also focus on new minimally invasive fixation methods. Although the manipulator fixator method described above is potentially minimally invasive, there are no true minimally invasive fixation methods available yet. When a conventional fixation plate is used for fixation, the technique is as invasive as a conventional corrective osteotomy procedure.

This thesis has shown many advantages of using computer-assisted surgical techniques. Further improvements in computer technology, reduction in production costs and development of better software programs will likely increase the presence of computers and 3D
imaging in the surgical field, which can already be seen as a trend in the current literature. Our research projects are a step forward in surgical preoperative planning and guidance. Future research will benefit from the concepts described in this thesis, and the studies will further contribute to improving corrective osteotomy surgery.