3D Druck zur Erstellung patientenspezifischer Implantate bei Azetabulumfrakturen

3D Print for the Creation of Patient-Specific Implants for Acetabular Fractures

Dissertation von Sebastian Martin Andreß

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Direktor:
Prof. Dr. med. Wolfgang Böcker
Prof. Dr. med. Boris Holzapfel

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Dekan:	Prof. Dr. med. Thomas Gudermann
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Sebastian Martin Andreß
München, August 3, 2022

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List of Abbreviations

3D three-dimensional. 1, 2, 7, 9, 11, 12, 13, 14, 17

ABS Acrylonitrile Butadiene Styrene. 9

AO Association for the Study of Internal Fixation. 6

CT Computed Tomography. 7, 11

FDM Fused Deposition Modeling. 9, 12, 19

HU Hounsfield Unit. 11, 16

MRI Magnetic Resonance Imaging. 7, 11

PLA Polylactic Acid. 9, 19

RSNA Radiological Society of North America. 14

SLA Stereolithography. 9

SLS Selective Laser Sintering. 10

UV Ultraviolet. 9

List of Publications

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Simon Weidert[*], Sebastian Andreß[*], Christoph Linhard, Eduardo M. Suero,
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3D Printing Method for Next-day Acetabular Fracture Surgery Using a Surface Filtering Pipeline: Feasibility and 1-year Clinical Results
International Journal of Computer Assisted Radiology and Surgery
Published: 02.01.2020

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[*] Authors have contributed equally and share first authorship

[†] Corresponding Author

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93. Jahrestagung der Vereinigung der Bayerischen Chirurgen e.V. 2016

1. Abstract

1.1 English

Acetabular fractures present a major surgical challenge due to their complex anatomic and functional features. The complex surgical approach, as well as incomplete intraoperative insight into pathology, complicates fracture management. In addition, inadequate reductions, local complications, and long trauma-to-operation time have a negative impact on patient outcome. The surgery is characterized by a flat learning curve, and the treatment outcome is correlative to the experience of the surgeon.

In recent years, additive production techniques as 3D printing have evolved significantly. This work aims to improve the quality of acetabular fracture treatment by using printed models.

A patient-specific model can be used here for three applications: Diagnostics, classification and surgical planning, and finally for patient-specific implant fitting on the model before or during surgery. Especially for the last field of application, model accuracy is of utmost importance. Since this is a new technology, there is currently no gold standard method for validating 3D printed medical models, although it is required by various scientific societies.

In this work, an open-source in-hospital pipeline was developed to enable printing, validation, and surgical planning. Furthermore, since treatment delay has a negative impact on patient outcome, a surface filter was developed that reduces printing time by 70%. This also allows fragments to be repositioned on the model without extensive dedicated manual segmentation work. The models could thus be produced in less than 12 hours on average. In addition, a novel validation method was developed that is specifically designed for the use on 3D printed models intended for use in surgery. This does not merely identify local defects, but provides the surgeon with safe zones in which the model has deviations below a definable threshold. This is done by means of ambivalent rigid registrations. Thus, the possible dislocation of an intrinsically correctly printed fragment is taken into account.

A total of more than 32 patients were treated by the presented pipeline, a final clinical study showed a satisfactory surgical result and patient outcome of all patients included.

1.2 German

Azetabulumfrakturen stellen aufgrund ihrer komplexen anatomischen und funktionellen Merkmale eine große chirurgische Herausforderung dar. Der komplexe operative Zugangsweg sowie die unvollständige intraoperative Einsicht auf die Pathologie erschweren die Frakturversorgung. Zudem haben eine unzureichende Repositionen, lokale Komplikationen, und eine lange Trauma-zu-Operationszeit einen negativen Einfluss auf das Patientenoutcome. Die Operation ist von einer flachen Lernkurve geprägt, und das Behandlungsergebnis ist korrelierend von der Erfahrenheit des Operateurs.
In den letzten Jahren haben sich additive Producktionsverfahren wie der 3D Druck deutlich weiterentwickelt. Diese Arbeit hat das Ziel, die Qualität der Behandlung von Azetabulumsfrakturen durch den Einsatz von 3D gedruckten Modellen zu verbessern.
Ein patientenspezifisches Modell kann hier für drei Einsatzbereiche verwendet werden: Die Diagnostik, die Frakturklassifikation und Operationsplanung, und schlussendlich auch zur patientenspezifischen Implantatanpassung am Modell noch vor oder während der Operation. Besonders für den letzten Einsatzbereich ist die Modellgenauigkeit von höchster Bedeutung. Da es sich um eine neue Technologie handelt, gibt es aktuell keine Gold-Standard Methode für die Validierung von medizinischen Druckmodellen, obwohl dies von diversen Fachgesellschaften gefordert wird.
In dieser Arbeit wurde eine open-source innerkrankenhäusliche Prozesskette entwickelt, welche sowohl den Druck, die Validierung als auch die Operationsplanung ermöglicht. Da eine Behandlungsverzögerung zudem negative Auswirkungen auf das Patientenoutcome hat, wurde ein Oberflächenfilter entwickelt, welcher die Druckzeit um 70% reduziert. Dieser ermöglicht außerdem die Reposition von Fragmenten am Modell ohne aufwendige manuelle Segmentierungsarbeit. Die Modelle konnten so gemittelt in unter 12 Stunden produziert werden. Des weiteren wurde eine neuartige Validierungsmethode entwickelt, welche speziell für den Einsatz an 3D gedruckten Modellen, welche für die Verwendung in der Operationsplanung vorgesehen sind, konzipiert ist. Diese weist nicht lediglich auf lokale Defekte hin, sondern bietet dem Operateur zusammenhängende, sichere Bereiche an, in welchen das Modell lediglich geringe Oberflächenabweichungen aufweist. Dies geschieht mittels ambiger, rigider Registrierungen. Somit wird die mögliche Dislokation eines an sich korrekt gedruckten Frakturfragments in Betracht gezogen.
Durch die vorgestellte Prozesskette wurden insgesamt über 32 Patienten behandelt,

eine abschließende klinische Studie zeigte ein zufriedenstellendes Operationsergebnis und Patientenoutcome aller eingeschlossenen Patienten.

2. Introduction

2.1 Acetabular Fractures

2.1.1 Characterization

Acetabular fractures are a subtype of pelvic fractures. However, due to the immediate proximity of the fracture to multiple surrounding anatomical structures, the complexity of their treatment is very high. Complications associated with poor patient outcome include nerve palsy, deep vain thrombosis, local infection, heterotopic ossification, osteoarthritis, and avascular necrosis [1]. Thus, poor outcome is associated with a poor surgical reduction result, however Letournel described a very flat learning curve, as he showed in his 4-year intervall [2]. Altogether this shows the importance of a good surgical result for a very complicated fracture treatment.

Anatomic Characteristics

The acetabulum is the socket between pelvis and femur. Through embryonic development, the pelvis itself consists of Os ileum, Os ischii and Os pubis, which arise from the nuclei of these three bones and fuse together in early childhood. Together, these parts form the acetabulum. The acetabulum itself is slightly tilted. Depending on the method of measurement of the acetabular alignment [3], an accepted range of inclination is from 40° to 45°, for anteversion from 15° to 20° [4]. The horseshoe-shaped lunate surface inside the socket is covered with cartilage, being the only surface that comes into contact with the femur during regular body movements and loads. The depressed fossa is not commonly covered with cartilage, as it does not stand in contact to the femur. Caudal to the acetabulum, the bony components of the acetabulum diverge to form the acetabular notch. It is covered by a transverse acetabular ligament along with a fat mass, however, vessels and nerves enter the joint in this area. Between the notch and the fossa arises the ligamentum teres, which enters the femoral head and carries an acetabular branch of the obturator artery. In addition, blood supply of the femoral head is provided

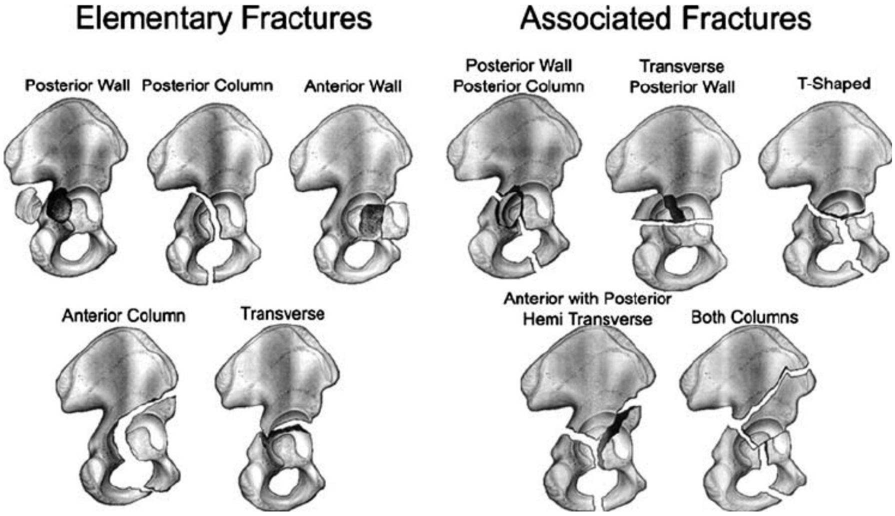

Figure 2.1: Classification of Acetabular Fractures by Letournel, drawings from Pagenkopf et al. [6].

by two other arteries ascending from the femoral neck [5].

Fracture pattern, Classification, and Epidemiology

Letournel and Judet divided acetabular fractures into elementary and associated types, each again with 5 subtypes [2]. Simple fractures consist of one fracture line, and the complex types are combinations of the simple types [6]. The classification is based on the embryonal concept of two columns: an anterior (Os pubis) and a posterior (Os ischium). It describes the pathway of the fracture line in relation to these columns as shown in Figure 2.1. Nowadays, the Association for the Study of Internal Fixation (AO) classification is more commonly used, that is based on Letournel's principles. However, it integrates the prognostic outcome of the corresponding fracture types [7].
The most prevalent cause of this fracture is indirect trauma, where force being applied through the femoral bone. The main mechanisms of injury are motor vehicle accidents, falls from height, and pedestrians being struck by a vehicle [8]. Two main direct pathomechanism apply for this fracture: with the femur being in flexion or extension. Indirect traumata during flexion in the femoral joint with, with force being applied axial to the femur, often cause a fracture in the posterior pillar, while a trauma during extension more often leads to a fracture in the anterior one [2].
From an epidemiological point of view, two patient populations are most frequently affected by this type of fracture: Young patients under 40 years of age and the elderly over 55 years of age. In young patients, high velocity injuries are the

leading cause of acetabular fractures. By far the most common cause of injury is a automobile accident resulting in a posterior wall fracture. In this combination, called *Dashboard Injury*, a seated person's knee is pushed against the dashboard of the vehicle, causing the femoral head to exert a force against the posterior portions of the acetabulum. Low-energy trauma, however, is most common in older patients. However, unlike to pelvic fractures, acetabular fractures are much less commonly associated with polytrauma and occur more frequent isolated [9].

2.1.2 Image Diagnostics

Several image diagnostic modalities are used for diagnosis and treatment decision: Three standard views are used for X-ray diagnosis[1]:

- Anterior-Posterior view: mostly used for the initial overview and in the diagnosis of fractures, as it is possible to compare the radiological morphology of both sides.
- Obturator Oblique view: useful to show the anterior column of the pelvis and the posterior wall of the acetabulum.
- Iliac Oblique view: for assessment of the posterior column and anterior wall of the acetabulum.

Nevertheless, Computed Tomography (CT) as a volumetric imaging technique is nowadays used as a standard for treatment planning. It allows better fracture inspection and indication for surgery. By generating a three-dimensional (3D) volume rendering from the imaging data, it furthermore helps to fully understand the fracture pattern and thus the classification, and assists in choosing the appropriate surgical approach, especially for less experienced surgeons [10]. In the diagnosis of insufficiency fractures, Magnetic Resonance Imaging (MRI) can help to detect medullary edema early; however, it is not used as a first-line diagnostic tool in trauma surgery [11]. All those imaging information is complementary and contributes to a complete understanding of the pathology.

2.1.3 Treatment Options

Treatment options for acetabular fractures range from conservative therapy to emergency surgery. Outcome goals differ depending on the patient's age [6]: While preservation of full joint mobility is of primary importance in young patients, in

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[1] Pelvis (Judet view), Radiopaedia
https://radiopaedia.org/articles/pelvis-judet-view-2
Retrieved on September 20th, 2021

older, multimorbid patients, the aim is to achieve the best and most stable result with only one surgery. However, in the case of a nondisplaced fractures with good joint congruency, nonsurgical treatment may also be considered.
In general, surgical approaches, in addition to nonoperative treatment, can be divided into posterior and anterior ones. A selection is described below.

Kocher-Langenbeck Approach [12] This approach is used to access the posterior part of the posterior column of the acetabulum. It is therefore preferred when the posterior column or wall must be reduced under direct vision. However, the anterior wall or column cannot be viewed directly with this approach. For access, the gluteal maximus muscle is split longitudinally, also the external rotator muscles must be detached from the trochanter major.

Modified Stoppa Approach [13] For accessing the pubic symphysis and the quadrilateral surface of the pelvis, the anterior wall, this approach is commonly used. In addition, a lateral window similar to a proximal *Ilioinguinal Approach* can be introduced, through which the entire anterior column can also be accessed. Access is gained through a transverse abdominal incision and splitting of the transverse abdominal muscle in the midline. Intraabdominally located muscular, neurovascular, and urogenital structures are retracted to allow the approach to the pelvic bone.

Ilioinguinal Approach by Letournel [14] It is used for the same indications as the Modified Stoppa Approach; however due to its invasiveness, it is used less commonly. Nevertheless it allows for extensive exposure of the whole anterior hemipelvis and is therefore an treatment option for complex fractures. The skin is incised from the pubic tuberculum to the iliac crest. Transection of the external oblique abdominal aponeurosis, as well as the internal oblique and transverse abdominal muscle along the inguinal ligament, down to the origin of the M. iliacus in the Fossa iliaca allow the access to the anterior pelvis.

2.1.4 Determining Factors of Surgical Outcome

Murphy et al. examined statistically relevant factors for a better or worse clinical outcome [15]: Fracture type, imperfect reduction leaving a gap of greater than 3 mm, and local complications lead to worse patient outcome. Meena et al. [16] further showed that a delay between injury and reduction of more than 2 weeks further worsens the outcome.

2.2 3D Print

2.2.1 3D Printing Technologies

In recent years, many new 3D printing technologies were invented, plus the technology itself has been improved. Nowadays, there are a large variety of different methods, all of which have their specific advantages and disadvantages [17]. In a review article, we summarized common printing methods, that seem applicable and relevant for clinical use [18]:

Vat Polymerization The more technical term for this technique is Stereolithography (SLA). It is the oldest established additive manufacturing process. Using Ultraviolet (UV) light, a liquid polymer resin is hardened at the desired areas. This process is done layer by layer and results in a smooth surface and high accuracy. However, the materials are expensive, the resulting model is very fragile, and the building process is comparatively slow. In addition, support structures have to be built, as the agent is not suitable as a stable base for already printed model parts.

Material Extrusion It is also known as Fused Deposition Modeling (FDM), a trademarked name by the company Stratasys[2]. Material, which is deformable at high temperatures, is fed through a hot nozzle and acquires its solid form through subsequent cooling. The nozzle, which is mounted on a movable printhead, places the hot and thus deformable material layer by layer at the desired areas. It is comparatively inexpensive and with the least maintainance work required, however very prone to errors, since the material distribution is dependent on the constantly applied pressure and heat. Furthermore the print speed is quite low. Support structures must be build for overhanging model parts. Commonly known material types are Polylactic Acid (PLA) and Acrylonitrile Butadiene Styrene (ABS).

Material Jetting This technique can be described as a combination of the two methods described above. Liquid material is directly jetted onto the desired areas layer by layer. For hardening, UV light or another curing method is used. It is very accurate, plus the models can be colored. Support material is also required.

Binder Jetting This technology currently offers the vast majority of printing materials available. It also is a layer-by-layer approach. Powder is scattered onto

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[2] FDM-Drucker, -Material und -Dienstleistungen
https://www.stratasys.com/de/fdm-technology
Retrieved on September 20th, 2021

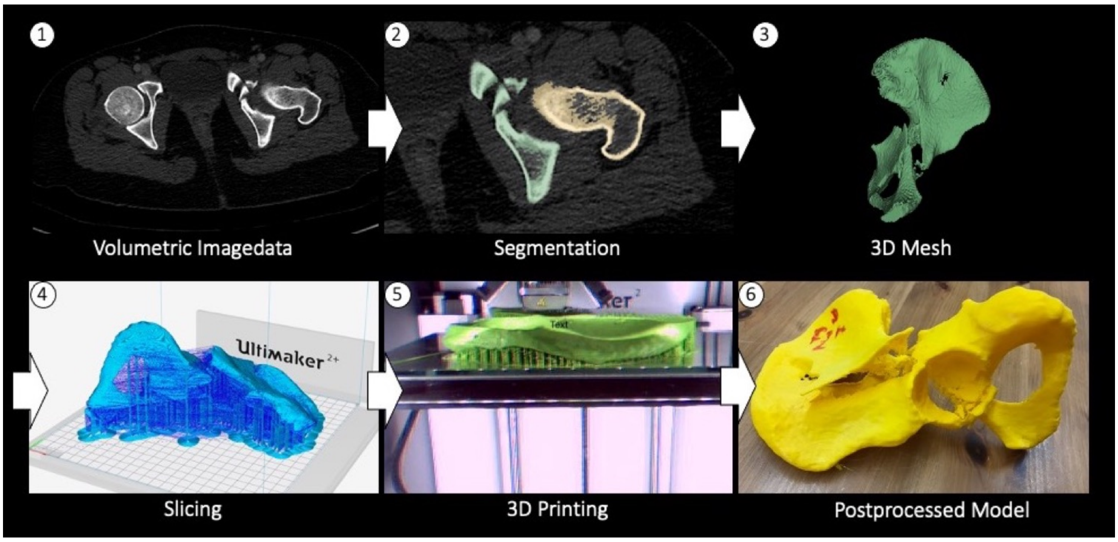

Figure 2.2: Phases of the Creation Process of a 3D Printed Model [18].

the buildplate or model respectively, which is hardened by distributing a binder over areas required for each layer. Multi-colored models are possible by coloring the binder. It is one of the fastest methods; no support structures are needed as the leftover powder supports overhanging parts. However, the post-processing can be labor intensive.

Powder Bed Fusion Several methods are subsumed under this term, one well-known example is Selective Laser Sintering (SLS). In general, powder of a desired material is scattered on the the printbed and hardened by applying heat to the desired areas; this is done layer by layer. Common types of heat distribution are electron beams or lasers. It also offers a wide range of possible materials, since no support structures are required as for *Binder Jetting*. However, the printing speed is quite low. In addition, depending on the model size and material type, this method can be quite expensive, as unused powder has to be discarded or reconditioned.

2.2.2 Bone Model Creation Process for Orthopedic Applications

As also described in our article [18], the creation of anatomical bone models is carried out in six phases, see Figure 2.2. Furthermore this is described in our second publication, as each in itself introduces certain errors that lead to inadequate bone modelling results.

1. **Image Acquisition** Patient images must be acquired with a 3D imaging modality. For bone replication in particular, CT imaging provides the highest currently available resolution and accuracy. However, the use of MRI is also possible as it can provide sufficient bone-tissue contrast. Non-fat-suppressed images are recommended [19].

2. **Segmentation** After image acquisition, areas to be printed (region of interest) must be masked, which is called segmentation. This is not to be confused with 3D image rendering, which creates models from a color and alpha lookup table for defined Hounsfield Unit (HU) values that can only be displayed on screens. However, this is not possible for 3D printing, so the segmentation is mandatory; it only separates between the categories inside or outside the desired region of interest.

   There are various software solutions that assist in the segmentation of medical 3D volumetric image data. The most known commercially available software solution is the Mimics Innovation Suite by Materialize[3]. Another growing competitor is ImFusion and their recently released ImFusion Labels software[4]. A comparable non-commercial competitors is 3D Slicer [20], an open-source software, originally developed by The Harvard University and maintained by Kitware[5].

   The following basic methods are used for the (semi-)automatized segmentation [21]:

   - Threshold Based: All areas within a given HU range are segmented. This method is simple and very efficient in most cases, especially when used for bone segmentation. However, manual processing is often necessary afterwards.
   - Clustering Based: These methods attempt to cluster associated areas based on similar criteria to thesholding, but also with respect to other clusters and continuity. Famous examples are *Growing-From-Seed* or *Level-Tracing*.

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[3] Mimics Innovation Suite
https://www.materialise.com/de/medical/software/mimics-innovation-suite
Retrieved on September 20th, 2021

[4] ImFusion Labels
https://www.imfusion.com/products/imfusion-labels
Retrieved on September 20th, 2021

[5] 3D Slicer
https://www.slicer.org
Retrieved on September 20th, 2021

   - Statistical Methods: This method works reliably for non-pathological bone anatomy without fractures. A *Statistical Shape Model* of the desired bone is fit to the region of interest [22].
   - Artificial Intelligence Based: A *Deep Learning* model is fit to recognize the region of interest. Lots of research is currently being focused on this technology, especially in the area of image processing, which is why segmentation tasks are progressively reliable and correct. Unfortunately, as for the *Statistical Shape Model*, problems still occur with uncommon fractures [23, 24]. However, this might be the most promising technology to fully automatize this process in the future.

3. **3D Mesh Generation** The volumetric 3D imaging scan is reconstructed in a specific orientation, e.g. in axial slices. After segmentation, each of these slices has a masked region of interest containing the bony structures, resulting in a stack of aligned images with associated labeled regions. However, depending on the slice thickness of the reconstruction, all these labeled images have to be combined to a 3D mesh. A mesh is a 3D object constructed from multiple polygons, very often triangles, as shown in Figure 2.3. There are several methods for this mesh computation, very well known is the (discrete) marching cube algorithm, originally invented by Lorensen and Cline in 1987 [25] and improved by Kenmochi et al. [26]. Here, the 3D volume is divided by several small cubes. Depending on the labeling of each edge of the cubes, a specific surface shape is generated, resulting in a closed surface mesh. Often this mesh gets further processed, e.g. smoothing might be applied [27].

4. **Slicing** Here the mesh is aligned to the optimal print position and orientation. Depending on the used printing technology, a broad contact basis to the printbed might be beneficial for the printing result, as well as trying to reduce overhanging parts. In addition, print settings as the speed, material densities, and layer thickness are defined. Finally, the optimized print path is calculated and written to a file format that can be read by the printer.

5. **Rapid Prototyping** This part requires a lot of time, e.g. for hemipelvic bone models models multiple hours to days, but runs largely autonomous. Depending on the intended usecase of the bone model, different technologies are advantageous to others. For in-house printing often FDM technology is used given the benefits described in subsection 2.2.1.

6. **Post-Processing** After printing, depending on the printing technique, the model has to be retouched e.g. by removing support structures. Manual

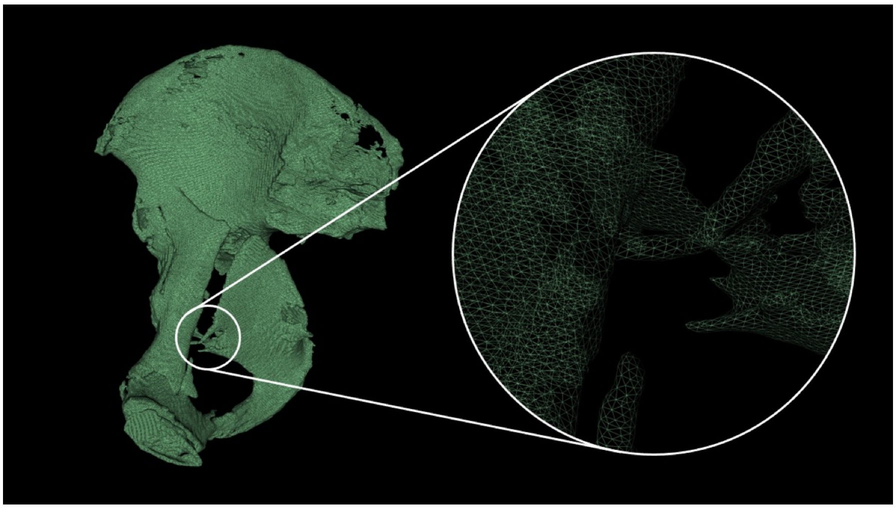

Figure 2.3: A 3D Mesh Model in Wireframe Presentation [18].

labour can be reduced by using water-dissolving materials for those structures. Minor visible errors can also be corrected here. Depending on the print material, chemical smoothing through vaporization of e.g. aceton can also be achieved in the post-processing process.

2.2.3 Current Use in Orthopedic Trauma Surgery and Problem Definition

Fields of Application and Adoption

The field of applications for 3D print in orthopedic surgery is steadily growing. Some of them are already applied in the clinical workflow [28]. Future usecases also include bioprinting and thus being able to print viable organs, however this currently is in an early stage of research [29].
In general, there are three advantages over a standard 3D rendering on a monitor: First, the haptical feedback can improve understanding of the pathology as well as physiological anatomy. As Wu et al. have shown that printed 3D models can be useful for anatomical eduction of students, especially for complex structures like the pelvis or the spine [30]. It also helps surgeons with the understanding of complex fracture patterns [31]. Secondly, fracture classification, especially on the pelvis, can be a challenging task; therefore the models can help in understanding fractures and with treatment decisions. And lastly, implants can be pre-fit prior to surgery using the model; authors report promising results with less blood loss and shorter surgery times [32, 33]. This could also be shown in more recently published

review articles [34, 35]. Table 2.1 summarizes different publications that used 3D print for improving surgeons fracture understanding as well as surgery planning.

Validation of 3D Printed Models for Medical Usage

The quality of the 3D printed model varies depending on the creation process. Therefore, among others, the Radiological Society of North America (RSNA) strongly recommends to validate a model prior to clinical use [36]. Two main techniques are currently used for model assessment [37]: The comparison of anatomical landmarks and the surface comparison after re-digitizing the printed model.

The first method does not consider the surfaces between these landmarks and is therefore not applicable when the model is used for implant pre-fitting to those surfaces. However, model proportions might be validated with this method very efficiently.

The other method compares deviations of the surface points after a re-digitization of the printed model. Therefore this newly digitized model must be placed digitally on top of the pre-print model, which is called registration, to then calculate the deviations. However, calculating the deviations is highly dependent on the registration itself; a bad registration will lead to larger surface errors. Therefore, Nizam et al. report in a meta-analysis about larger measurement uncertainty than actual model deviation error when validating 3D printed bone models [38].

2.3 Objective of this Work and Contribution by the Author

The objective of this work was to develop an in-house pipeline that allows 3D printing of acetabular fractures within 24 hours for acute trauma care. The printed models were then used for surgical planning of fracture treatment, and in the course of this also to produce patient-specific implants for fitting reduction-plates to the models preoperatively. The complete pipeline is open-source and has been used by several other hospitals.

Two factors were critical for which this work solved: Time from trauma to treatment, and accuracy as well as the validation of the printed models.

Finally, the methods were applied to the treatment of over 32 patients, and the clinical study was published.

2.3.1 Manufacturing Process

Only open-source software was used to produce the models, in large parts the software 3D Slicer [20]. Here, the CT images of the patient required for the

Table 2.1: Publications addressing 3D print for orthopedic surgery. Content from our Article [18].

Author (Year)	Region	Clinical Content
Brouwers (2018)	Hemipelvis	Classification, surgical strategy of 20 acetabular fractures of 7 experts: X-Ray, CT, 3D-CT vs. 3D-Print
Chana-Rodriguez (2016)	Hemipelvis	Case Report: preoperative planning, acetabular fracture
Corona (2018)	Tibia	Case-Controll-Study, pseudarthrosis of tibia (10 vs. 10 Cases)
Debarre (2012)	Tibia, Schulter, patellofemor Joint	Case-Reports (3): tibial pseudarthrosis, planning of trochleoplastie of the knee
Frame (2012)	Radius, Ulna	Case-Report: pediatric pseudarthrosis of forearm
Giannetti (2017)	Tibia	Prospective Cohort-Study: tibial fracture, ORIF with vs. without 3D print
Lim (2018)	Hemipelvis	Case-Reports (5): Classification of acetabular fractures
Maini (2018)	Hemipelvis	Randomized Controlled Trial: Prebending of reduction plates for aceatbular fracture
Wu (2018)	Spine, Pelvis, Extremities	Fracture understanding
Yang (2017)	Ellenbow	Randomized Controlled Trial: Elbow fracture with vs. without 3D print

creation were initially imported. In a second step, the segmentation was done by thresholding (selection of the bone on the basis of its HU), which was completed by manual post-processing.

During the process, it became apparent that the threshold often only provides inaccurate results, and in particular often did not mask the entire bone, leaving out sponge-like holes in the cancellous bone. This resulted in a 70% increase in printing time. To overcome this, a solidification filter, that we denote as *Surface Wrap Solidify*, was created in this work, which is already being widely used in the community, including in further anatomical areas[6]. The complete pipeline as well as the filter were made publicly available on GitHub[7]and added to the App Store of 3D Slicer for easier use. The models were printed in-house by an Ultimaker 2+, after slicing with the Cura software.

This filter was constructed, developed, and evaluated by S. Andreß and is introduced in the first paper, funding required for its evaluation was acquired by Dr. Weidert.

2.3.2 Validation of the Models

Since the models were further used for the production of patient-specific implants, a validation method was searched for in the second part of this work. As 3D printing is a relatively new technology in medicine, there is no gold standard validation method defined yet. A paper search did not yield a method suitable for the usecase, although validation is demanded in several professional societies as shown above.

Thus, a new validation method was developed in this work, which we denote as *Similarity Subgroups Registration.* This method is specifically designed for detecting and classifying errors that can occur in the 3D printing process of bone models. Furthermore, this method differs from current methods in one particular respect: It offers the surgeon not only the defects themselves, but also shows him safe zones. Since errors were often caused by the individual parts breaking off (e.g. when the model was detached from the printing table), these otherwise were completely rejected as faulty in conventional methods. With the concept of Safe Zones, detached parts can be declared acceptable as long as they are used as parts in themselves and not in conjunction with the entire model.

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[6] 3D Slicer, Discourse Forum, Results to the Surface Wrap Solidify Module
https://discourse.slicer.org/search?q=WrapSolidify
Retrieved on September 20th, 2021

[7] Similarity Subgroups Slicer Module, GitHub Repository
https://github.com/sebastianandress/Slicer-SurfaceWrapSolidify
Retrieved on January 2nd, 2020

The code for this has also been open-sourced and made easily available in the 3D Slicer App Store[8].

For this second paper, the same patient data as for the first paper were used. The method was invented and developed by S. Andreß. It conclusively was evaluated by F. Achilles and S. Andreß. Patient data was prepared by J. Bishoff, Dr. Kußmaul and S. Andreß. Funding was acquired by Dr. Weidert and Prof. Böcker.

2.3.3 Clinical Trial

In a clinical trial 32 patients were included. 3D models of each of these patient's acetabular fractures were created and used for surgery planning and implant fitting. 20 of these patients subsequently underwent surgery. The surgeries were planned on the basis of the models and implants were adapted to the models pre- or intraoperatively. 12 of these patients underwent further follow-up examinations to measure the surgical outcome.

The models were created by S. Andreß. Preoperative planning and implant fitting was performed by all authors. Intraoperatively, the models were each placed in a sterile plastic bag and were used for further orientation and implant readjustment. The main surgeons were Prof. Böcker and Prof. Kammerlander. The clinical follow-up examinations were primarily conducted by Dr. Linhart, Dr. Greiner and Dr. Becker, study planning and statistical evaluation was done by Dr. Suero and S. Andreß, funding was acquired by Dr. Weidert and Dr. Becker.

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[8] Similarity Subgroups Slicer Module, GitHub Repository
https://github.com/sebastianandress/Slicer-SurfaceFragmentsRegistration
Retrieved on August 1st, 2021

3. 3D Printing Method for Next-day Acetabular Fracture Surgery Using a Surface Filtering Pipeline: Feasibility and 1-year Clinical Results

Abstract

Introduction In orthopedic surgery 3D-printing is a technology with promising medical applications. Publications show promising results in acetabular fracture surgery over the last years using 3D-printing. However, only little information about the workflow and circumstances of how to properly derive the 3D-printed fracture model out of a CT scan are published.

Material and Methods We conducted a retrospective analysis of patients with acetabular fractures in a level-1-trauma center. DICOM-Data was preoperatively used in a series of patients with acetabular fractures. The 3D-mesh models were created using 3D Slicer with a newly introduced surface filtering method. The models were printed using PLA material with FDM-printer. After reduction of the printed model, the acetabular reconstruction plate was bent preoperatively and sterilized. A clinical follow-up after 12 months in average was conducted with the patients.

Results 12 patients included. Mean printing time was 8:40 h. The calculated mean printing time without applying the surface filter was 25:26h. This concludes an average printing time reduction of 65 percent. Mean operation time was 3:16 h and mean blood loss was 853 ml. Model creation time was about 11 min and mean printing time of the 3D-model was 8:40h, preoperative model reduction time

was 5 min on average and preoperative bending of the plate took about 10 min. After 12 months, patients underwent a structured follow-up. Harris Hip Score was 75.7 points, the Modified Harris Hip Score 71.6 points and the Merle d'Aubigne Score 11.1 points on average.

Conclusion We presented the first clinical practical technique to use 3D-printing in acetabular fracture surgery. By introducing a new surface filtering pipeline, we reduced printing time and cost compared to current literature and the state of the art. Low costs and easy handling of the 3D-printing workflow make it usable in nearly every hospital setting for acetabular fracture surgery.

Reference

Simon Weidert, Sebastian Andreß, Christoph Linhard, Eduardo M. Suero,
Axel Greiner, Wolfgang Böcker, Christian Kammerlander, Christopher A. Becker
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4. A Method for Finding High Accuracy Surface Zones on 3D Printed Bone Models

Abstract

The use of three-dimensional (3D) printing for surgical applications is steadily increasing. Errors in the printed models can lead to complications, especially when the model is used for surgery planning or diagnostics. In patient care, the validation of printed models should therefore be performed routinely. However, there currently is no standard method to determine whether the printed model meets the necessary quality requirements. In this work, we present a method that not only finds surface deviations of a printed model, but also shows high accuracy zones of a potentially corrupted model, that are safe to be used for surgery planning.

Our method was tested on printed patient bone models with acetabular fractures and was compared to two common methods in orthopedics, simple landmark registration as well as landmark plus subsequent iterative closest point registration. In order to find suitable parameters and to evaluate the performance of our method, 15 digital acetabular bone models were artificially deformed, imitating four typical 3D printing errors. A sensitivity of over 95% and a specificity of over 99% was observed in finding these surface deformations. Then, the method was applied to 32 printed models that had been re-digitized using a computed tomography scanner. It was found that only 25% of these printed models were free of significant deformations. However, focussing on two common implant locations, our method revealed that 72% of the models were within the acceptable error tolerance. In comparison, simple landmark registration resulted in a 9% acceptance rate and landmark registration followed by iterative closest point registration resulted in a 41% acceptance rate.

This outcome shows that our method, named *Similarity Subgroups Registration*, allows clinicians to safely use partially corrupted 3D printed models for surgery

planning. This improves efficiency and reduces time to treatment by avoiding reprints. The similarity subgroups registration is applicable in further clinical domains as well as non-medical applications that share the requirement of local high accuracy zones on the surface of a 3D model.

Reference

Sebastian Andreß, Felix Achilles, Jonathan Bischoff, Adrian Cavalcanti Kußmaul,
Wolfgang Böcker, Simon Weidert
A Method for Finding High Accuracy Surface Zones on 3D Printed Bone Models
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