Digitalisation and volume estimation of bone grafts using image-less navigation system: A feasibility study

Franziska Kofler

***Abstract*—The aim of this study was to estimate the volume of bone grafts using a imageless navigation system and to create an overview of the potential volume sizes of autogenous bone graft obtained from the iliac crest, tibia, fibula, calcaneus, olecranon and radius.**

29 different bone segments were digitised, gathering point cloud data with a navigation system and volumes were calculated using the Delaunany-triangulation. Articles were reviewed to quantify the maximal volume of bone available for from the different donor sites. The method of digitization of bones using a image less navigation system offers satisfactory results when digitising relatively simple shapes and is easy and fast to conduct. Digitizing concave shapes leads to more imprecise in volume calculation. The results of the volume calculation may be falsified by gathering airpoints. The maximal volume size can be obtained from the posterior iliac crest with 88ml. The second largest amount of bone graft can be harvested form the tibia with 70 ml. From the calcaneus a volume of 10 ml can be obtained. The radius with 3.6 ml and the olecranon with 3.5 ml can provide almost the same maximal volume. The used digitization technique may be helpful for the estimation of volumes and for choosing the ideal graft and donor site. For large bone defects the iliac crest is recommended as the largest volume can be obtained. For smaller volumes it is recommended to harvest bone from a local donor site.

***Index Terms*—allograft, autograft, bone defect, abstract, template.**

I. INTRODUCTION

THE human skeleton has the extraordinary ability to regenerate itself after injury and return to its original form and function. The only organ that is also capable of self-regeneration is the liver. However, the circumstances for spontaneous bone healing are not always optimal.Yet even with the efficacy of modern internal fixation techniques, infection, poor vascularity, malnutrition and substantial bone or soft tissue loss can impede effective osteosynthesis [1]. Bone grafting is used as a surgical method to augment bone healing and to reconstruct or replace bone defects. This bone defects are often caused by a trauma with complicated fractures or the treatment of bone tumors. Bone grafts are used to treat musculoskeletal disorders, to strengthen arthrodeses and to replace skeletal defects [2]. With over two million surgeries per year worldwide bone grafting is one of the most frequent tissue transplantation procedure [3]. The gold standard for this procedure is the use of autologous bone since all required properties in bone regeneration in term of osteoinduction, osteoconduction and osteogenesis are combined. Bone allografts are often used for orthopedic surgeons since they are available in large quantities and in various forms [4]. The choosing of the right bone graft is still a big challenge to surgeons. The preference is mostly given to a cortical, cancellous or a corticocancellous autograft from donor sites. The availability of such autografts is limited and involved with potential complications. The consideration for selecting the right bone graft include availability, characteristic capabilities, patient morbidity, potential disease transmission, immunogenicity and cost variability. The following properties of bone graft are crucial for the decision of the graft [5]. Ideally the chosen bone graft should provide:

Structural support: There is quite an important difference in bone graft regarding the structural strength the graft can provide. Cancellous grafts give poor structural strength and can only resist compression to a certain degree. Cortical grafts are able to withstand mechanical loads and can provide structural strength. Mechanical properties of the graft varies according to the donor and the harvested bone quality. If the bone is already older or osteoporosis the quality of the graft is reduced regarding structural strength and resorption propensity of the graft [6].

Osteoconduction: describes the microscopic connective tissue matrix. The osteocunductive process allows the ingrowth of host capillaries, perivascular tissue and mesenchymal stem cells into the implanted scaffold passively. All bone substitutes and bone grafts provide this property. Without a scaffold the ingrowth and bone formation would be inhibited [1], [5].

Osteoinduction: describes the protein mediated proliferation, recruitment and differntiation of cells. Host mesenchymal stem cells are differentiated into chondroblasts and osteoblasts.If the bone graft provides osteoinductive properties it contains one or more bone morphogenetic properties[1], [5].

Osteogenesis: refers to the synthesis of new bone by the cells of the graft. Growth factors, cellular elements and matrix are required for this process. Mesenchymal stem cells, osteoblasts and osteocytes are involved in the process. Only fresh autologous grafts are typically involved in the osteogenesis. For other modalities of bone grafting cells may be transplanted from other parts in the body [1], [5].

F. Kofler is student of the Master's program "Medical Technologies" at MCI, Innsbruck, Austria, e-mail: f.kofler@mci.edu.

Several forms of bone grafts can be distinguished, such as autologous grafts, allografts or synthetic bone grafts [7]. An autologous bone graft is harvested from one anatomical part and transplanted to another body part within the same individual [4]. Autografts are commonly used because of their osteoconductive framework, the osteogenic potential and the low risk for the transmission of bacterial or viral diseases. The quantity and quality of autografts is limited and the associated blood loss and the high morbidity rate of the donor-site is clearly a disadvantage. However this type of bone graft is considered as the gold standard in the treatment of bone defects [4]. The autografts are mostly harvested form the posterior superior iliac spine, the iliac crest, the distal femur, the distal or proximal tibia, olecranon or distal radius [5]. Cortical bone grafts is recommended for the treatment of structural defects. It provides minimal osteogenetic and osteoinductive properties but high osteoconductive potential. The matrix of the cortical bone graft is dense and therefore optimal to provide immediate mechanical and structural stability. on the other hand cancellous bone grafts provide no structural strength but osteoconductive, osteoinductive and osteogenic properties. The cancellous autograft can be harvested with functional osteocytes which host mesenchymal stem cells (MSC). The MSCs are able to differentiate into osteoblasts and makes this graft option highly osteogenetic and the graft is able to be vascularized within the first days. Therefore autogenous cancellous bone graft is best suited for the treatment of nonunions or arthrodesis. Corticocancellous bone grafts is able to provide mechanical and structural strength as well as providing osteogentic and osteoinductive capabilities. The iliac crest is the most frequent harvesting site of corticocancellous bone. Another possibility to improve the incorporation of the graft are vascularized grafts. The previous mentioned autogenous graft forms can be harvested with a vascular pedicle. Especially when bone defects over 12cm requires a graft a free vascularized graft is highly recommended [5].

Allografts are grafts which have been extracted from donors or cadavers.After the extraction the bones are either fresh frozen, irradiated or deep fried. The advantage of this grafts is the good availability in those countries where bone banks are present. A disadvantage is the relatively slow incorporation of the allograft, a high pseudoarthrosis range and the potential risk of infections or viral disease transmission. The Gamma radiation or freezing method is not sufficient to eliminate the human immunodeficiency virus (HIV) infection from allografts [8]. Several forms of allografts can be distinguished. Cancellous allografts are mostly produced in the form of cuboid chips called "croutons". They are mainly used in the filling of osseus defects, such as in retroacetabular osteolysis for within a total hip arthroplasty. Cancellous allografts have the disadvantage of providing little mechanical strength, little healing support due to their preparation, and no growth factors to support osteoinduction. Cortical allografts are readily available, can be used in combination with many fracture repair methods, and provide rigid structural support. Like cancellous allografts, they are used to fill larger defects. Due to their stability, weight bearing can be applied early and before incorporation of the grafts. For this reason, they are well suited for periprosthetic hip fractures to provide stability to the femoral shaft [9]. Demineralized bone matrix (DBM) is readily available and and one of the most commonly used form of allografts. DBM are used for the filling of bone defects, grafting of nonunions or as an adjunct to spinal fusion interventions. Their osteoinductive properties are better than those of cortical or cancellous allografts and are able to stimulate healing through the differentiation of MSCs to osteoblasts[10]. This capability is highly dependent on the preparation process of DBms. Techniques were alcohol, lactic acid, acetic acid or nitric acid are involved are likely to have a negative effect on osteoinductivity. The most of the DBM are treated with hydrochloric acid or are admixed with cancellous or cortical bone chips to provide additional osteocoinductive properties[1].

II. Methods

A. Digitalization and volume estimation

For the 3D data acquisition, 29 different bones were selected from real and synthetic bones. Some digitized bones already showed defects. Beside the bones an allograft out of polyurethane in form of a acetabulum (Sawbone Nr1306, Sawbone Pacific Research Lab- oratories, Vashon, WA USA) was digitized. Since the extremities are most frequently affected for bone transplants in the field of orthopedics, the focus was placed primarily on bone parts of the upper and lower extremities. TableI shows the selected bones that were digitized. For the digitization of the bone structures a Stryker eNlite Navigation System (Stryker Corporation, Kalamazoo, Michigan, USA), a Stryker 6007-11 Pointer and a nGenius tracker was used (Mean trueness values of 0.058mm with standard deviation 0.033mm [11]). For the calibration of the camera of the navigation system the two trackers are placed in the field of view of the camera. The trackers serve as orientation points in space for the camera in order to guarantee the most accurate acquisition of coordinates. The software OrthoCad (OrthoCad, Version2016, Klemm Martin,Germany) was used to generate and display the point cloud data. Until now, orthopedic interventions were mostly performed conventionally and manually; it often happens that the preoperative plans have to be discarded because the intraoperative conditions do not match the plans and thus cannot be performed. The OrthoCad system is a general platform that makes it possible to plan intraoperative computer-based surgical steps. The system is based on interoperative positioning of bone trackers and the system concept is based on a CAD system. With this system, primitives, e.g. lines, points or planes can be digitized intraoperatively on the patient's bone. These primitives can be assembled into complex objects. The digitization of generated point clouds makes it possible to scan the bone of a patient[12]. The OrthCad software interface shows a virtual room. The Digitizing Menu on the left allows the surgeon to select different objects for the tip of the pointer. The status bar in the lower left corner shows the availability of the registered landmarkers and pointers. If the indicator is red, the tool is not in the field of view of the camera. In the view menu in the lower left corner the viewing angle can be changed. So the viewing angle of the camera, the surgeon or the pointer can be selected (Fig. 1). To calculate the volume out of the point cloud data the Delaunay triangulation algorithm in MATLAB®(MATLAB, Version R2014a, MathWorks, Natick, Massachusetts, USA) was used.The initial point cloud data can be shown in a coordinate system and the surface of the digitized object can be shown in MATLAB.

TABLE I
3D GENERATED BONES

Bone	Part	Shape
Femur	Caput	spherical
Femur	Epiphysis distalis	cylindrical
Calcaneus	Whole bone	wedge
Fibula	Corpus	cylindrical
Humerus	Corpus	wedge
Tibia	Corpus	wedge
Tibia	Corpus	wedge
Tibia	Corpus	cylindrical
Digitus manus V	Phalanx distalis	cylindrical
Fibula	Malleolus lateralis	cylindrical
Allograft	Acetabulum	not defined
Femur	Caput	spherical
Digitus pedis I	Corpus ossis metatarsi	cylindrical
Digitus manus II	Phalanx proximalis	cylindrical
Os cuboideum	Whole bone	ellipsoid
Ulna	Olecranon	cylindrical
Os illium	Ala ossis ilii	cylindrical
Os coxae	Os ischii	cylindrical
Os scaphoideum	Whole bone	ellipsoid
Patella	Whole bone	ellipsoid
Radius	Caput radii	cylindrical
Os sacrum	Whole bone	not defined
ulna	Corpus	cylindrical
Tibia	Condyli	not defined
Tibia	Corpus	cylindrical
Vertebrae lumbales	Corpus	not defined
Femur	Collum femoris	cylindrical
Femur	Condyli	not defined
Digitus manus III	Os metacarpale	cylindrical

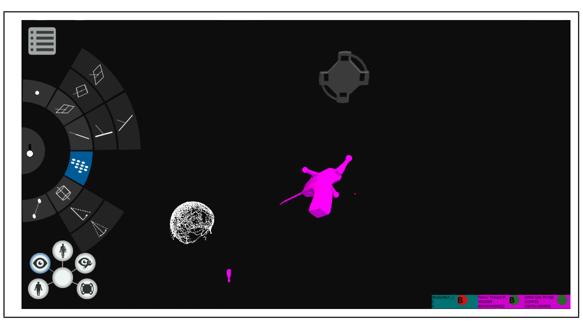


Fig. 1. Interface of the OrthoCAD application. The Status bar shows the status of the registered tools. If the status bar shows the color red for a tool it is not placed in the field of view of the camera and therefore can not be used. In the scene a digitized femur head, the pointer and the tracker (violet) is shown.

B. Empirical investigation on potential volume sizes of autologous bone grafts

In order to gain a complete overview of the current state of research on the volume sizes of autografts for the iliac crest, fibula, calcaneus, radius and tibia a systematic literature search for relevant studies was conducted in the database of Pubmed (date of literature search: June 2021). The literature search in the electronic databases was based on a systematic combination of the keywords: autograft, bone graft harvesting, volume, corresponding donor site. The search terms were performed and yielded summed up 730 results in the database of PubMed. The 730 articles were first screened by title and the publications which were not addressing the research question were excluded. In the next step the remained abstract were screened by abstract and again publications which were not addressing the research question were excluded. Sixty publications remained for the full text screening where more articles were excluded because no relevant information was found. Finally 27 articles were included in this study.

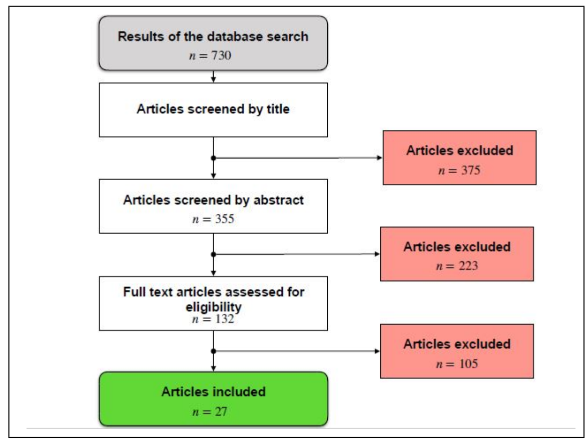
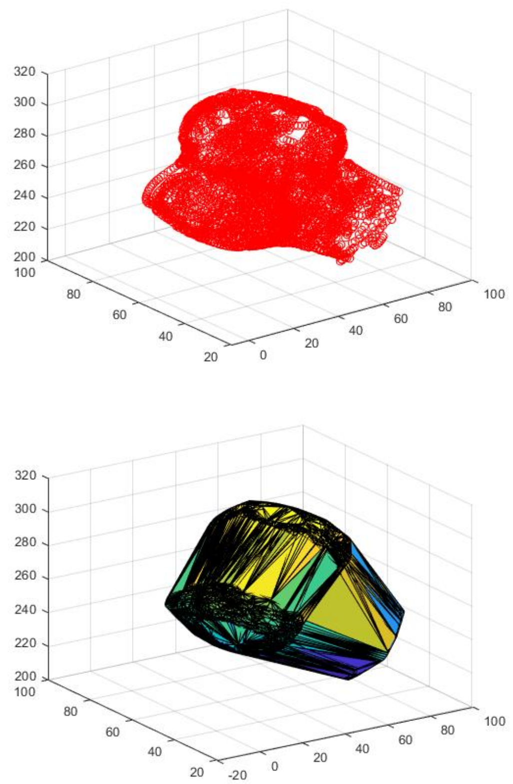


Fig. 2. Flowchart of the systematic literature research

III. RESULTS

A. Digitization and volume estimation

The selected bone segments were digitized and the volume was calculated in Matlab. Fig. 3 (a) shows the generated point cloud in MATLAB. The time for the digitization process for a single bone segment was, depending on the size of the bone segment, between 1 and 10 min. Fig. 3 (a) shows the generated surface of the femoral condyles. The femoral condyles have a concave surface. This is difficult for the algorithm to calculate the volume, because it is only able to represent convex shapes. The difference can be clearly seen when comparing fig. 3 (a) and (b). The facies intercondylaris, which normally lies between the lateral and medial condyle, is not represented. For this reason, the calculated volume of bone segments with concave structures may differ by a few cm^3. Figure 4 shows a digitized segment of the fibular bone. During the digitization process air points were gathered. The algorithm is not capable to filter those points and includes them for the surface calculation. Therefore the calculated volume and surface is larger than expected. The calculated volumes are shown in table II. The smallest bone part with the lowest volume was the phalanx distalis of the digitus manus V with 1,96 cm^3. The largest digitized bone part is the iliac crest with 696,83 cm^3.



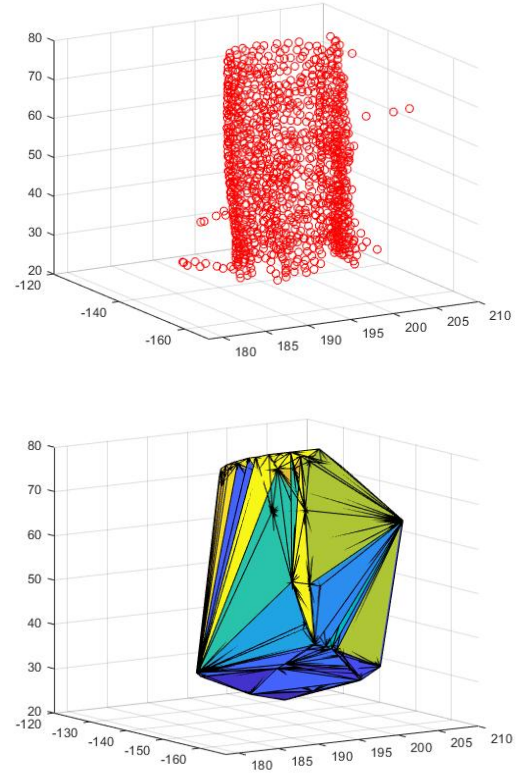
[a]

[b]

Fig. 3. (a) Gathered point cloud data of the femurcondyles (b) Calculated and visualized surface of the femorcondyles from the point cloud data using Deauny triangulation

TABLE II
RESULTS OF THE VOLUME MEASUREMENT

Bone	Part	Shape	Volume $[cm^3]$
Humerus	Corpus	wedge	13,91
Ulna	Corpus	cylindrical	25,7
Ulna	Olecranon	cylindrical	28,27
Radius	Caput radii	cylindrical	7,21
Os cuboideum	Whole bone	ellipsoid	21,89
Os scaphoideum	Whole bone	ellipsoid	2,42
Digitus manus II	Phalanx proximalis	cylindrical	4,5
Digitus manus III	Os metacarpale	cylindrical	6,72
Digitus manus V	Phalanx distalis	cylindrical	1,96
Os illium	Ala ossis ilii	cylindrical	696,83
Os coxae	Os ischii	cylindrical	22,99
Os sacrum	Whole bone	not defined	515,71
Vertebrae lumbales	Corpus	not defined	33,62
Femur	Caput	spherical	108,55
Femur	Epiphysis distalis	cylindrical	276,70
Femur	Caput	spherical	76,9
Femur	Collum femoris	cylindrical	23
Femur	Condyli	not defined	230,52
Patella	Whole bone	ellipsoid	31,4
Fibula	Corpus	cylindrical	12,64
Fibula	Malleolus lateralis	cylindrical	16,44
Tibia	Corpus	wedge	23,78
Tibia	Corpus	wedge	24,91
Tibia	Corpus	cylindrical	31,36
Tibia	Condyli	not defined	95,87
Tibia	Corpus	cylindrical	55,23
Calcaneus	Whole bone	wedge	142,42
Digitus pedis I	Metatarsus	cylindrical	3,5
Allograft	Acetabulum	not defined	31,65



[a]

[b]

Fig. 4. (a) Point cloud data of the fibula (b) calculated surface of the fibula

B. Maximal volume sizes

1) Bone graft harvesting form the iliac crest: The most commonly site for corticocancellous grafts is the posterior or anterior iliac crest [13]. From the iliac crest unicortical, bicortical, tricortical or corticancellous segments can be harvested [14]. The volume which can be harvested is limited and avarages 30 cm^3 posteriorily and 13 cm^3 anteriorily.
For the iliac crest there are two possibilities: harvesting the graft material from the anterior or the posterior iliac crest. Harvesting cortical bone grafts from the anterior iliac crest, requires less intraoperative time but also less bone can be harvested compared to the posterior iliac crest. Burk et al. [15] conducted a large cadaveric study investigating the maximum autogenous bone volume obtained form the anterior iliac crest and the posterior iliac crest. The largest uncompressed volume harvested from the iliac crest was 48 ml from the main segment of the posterior iliac crest and 13 ml from an additional 1cm segment. On average 34 ml of uncompressed autologous bone and 25 ml of compressed bone could be harvested from the posterior iliac crest. From the uncompressed bone graft 26% was blood or fat, that are not needed for bone grafts. The grafts were obtained over a surface area yielding an average of 28.40 cm^3 from the posterior iliac crest and 30.52 cm^3 from the anterior iliac crest. Singh et al. [16] reported an average volume of 27 cm^3 of cancellous bone graft in a retrospective study of 46 patients with autologous bone graft harvesting of the anterior iliac crest. With the use of an acetabular reamer technique

larger volumes up to 90 cm^3 can be harvested. If the graft volume is harvested from a single iliac crest a combination of anterior and posterior crest harvest can be performed. Despite the associated increased blood loss, donor-site morbidity, operating and hospitalization time iliac crest is the most considered autograft and therefore the gold standard for autologous bone grafts. Autologous grafts from the iliac crest have high fusion rates (92%) [17]. From the anterior iliac crest corticocancellous or cancellous grafts can be harvested. Obtaining bone form the anterior iliac crest should be used if the required volume is less than 20-30 cm. The obtainable volume is limited due to safety reasons. At least 3 cm of the anterior superior iliac spine should stay intact to avoid injuries of the inguinal ligament and the sartorius muscle. The surgeon should avoid the lateral femoral cutaneous nerve, which often can have anomalous course [14]. The iliac tubercle is located 5 cm posteriorly from the anterior superior iliac spine and provides high amount of cancellous bone to be obtained [5].

Wolfe and Kawamoto [18] described a technique where the inner and outer sites of a central graft are separated and a block of autogenous bone up to 10 cm x 8 cm can be harvested. From the posterior site of the iliac crest large volume of bone can be harvested.

Boucree et al. [19] performed bilateral bicortical osteotomy on 55 cadavers to harvest 110 posterior iliac crest bone grafts. The average of the osteotomy widths, lengths and depths were 5.5, 7.4 and 1 cm, respectively. The average volume of the obtained grafts was 10,6 cm^3. The maximum bone graft harvested within this study was 41 cm^3. This maximal volume is the maximum graft size that could be harvested without causing harm to the bordering vital structures. Studies reported that a larger harvested graft size increases the rate of major complications [15]. The author noted also that anatomical variations are quite common and surgeons have to be aware of them to void donor-site morbidity [19].

Ahlmann et al. [20] reviewed 108 iliac crest grafting surgeries from 1991 to 1998 to treat chronic osteomyelitis and recorded the volume of bone graft harvested from the iliac crest. The mean graft volume harvested was 54.53 cm^3 from the anterior iliac crest and 55.12 cm^3 from the posterior site. Within this study the authors recommend to harvest the graft whenever possible from the posterior iliac crest. The mean total blood loss and the complication, such as haematoma, sensory disturbance and pain are significantly lower when bone grafts are harvested from the posterior iliac crest. Overall the average volume for anterior and posterior iliac crest grafts has been identified to be 13 and 30 cm^3.

2) Bone graft harvesting form the tibia: The proximal tibia is a common donor for autogenous bone harvesting and together with the anterior and the posterior iliac crest one of the three most common used donor sites for autogenous cancellous bone grafting. The volume of cancellous bone which can be harvested form the proximal tibia have been reported in various articles and clinical reports. An advantage for using the proximal tibia as a bone donor is the low complication rate in comparison to the anterior iliac crest with quite high complication rates. Although the proximal tibia is not considered when a significant amount of bone is required because the volume, which can be harvested is limited. The cortical amount of bone that can be harvested is low because the tibia is an important weight bearing part of the knee joint. The consequence of harvesting to much bone could cause severe complications, such as fractures [27], [21]. Engelstadt et al. [21] reported an average volume of harvested cancellous bone from the proximal tibia as 11.3 ml. The authors recommend leaving 1cm of cancellous bone at the tibia plateau intact to guarantee the integrity for weight bearing.

Dalal et al.[27]described the proximal tibia metaphysis as a useful site for harvesting autogenous cancellous bone graft with low morbidity and complication rates. In young adults up to 70 cm^3 of cancellous graft volume can be obtained and is a suitable graft choice for foot and ankle surgeries [14], [27]. The average volume of harvested cancellous bone from the proximal tibia is approximately 25 cm^3 [14].

Herford et al. [28] compared the amount of bone graft available from the lateral site of the tibia to the medial site of the tibia. Comparing the lateral and the medial approach there was no significant difference in the volume of the bone graft found. The mean volume of obtained bone graft for the lateral site was 25 ml and 24.9 ml for the medial site of the proximal tibia. Therefore both approaches are recommended for bone harvesting of the posterior proximal tibia.

Nikolopulos et al. [26] determined the volume of bone that can be obtained from the proximal tibia based on computed tomography imaging on a three dimensional medical imaging model. The volume of cancellous tibial bone ranged from 16.26 ml to 69.56 ml with a mean volume of 38.60 ml.

Alt et al. [29] obtained compressed volumes ranged from 3.5 to 6.6 ml and a average volume of 5.39 ml of tibial cancellous bone from nine cadaveric bones. They mentioned, that the tibia can not offer cortical or corticocancellous bone because of the potential to cause mechanical destabilisation in the metaphysis of the proximal tibia. Therefore the proximal tibia as a bone graft donor is only recommended when cancellous bone is needed. They reported that the proximal tibia can offer a sufficient volume of cancellous bone for many applicationswithout the risk of postoperative fractures.

Catone et al. [30] harvested cancellous tibial bone from 21 patients which underwent a reconstructive procedure for their maxillofacial.The average of obtained compressed bone form the proximal tibial metaphysis was 25 ml, within the range of 10 to 42 ml. On the second postoperative day, most of the patients were already able to bear weight on the donor leg. Most of the patient needed additive to the tibial graft beacause the obtained volume of the tibia bone was not enough to cover large maxillofacial procedures.Therefore for procedures which requires an amount greater than 40 ml the bone should be harvested from the iliac crest.

3) Bone graft harvesting form the fibula: The fibula is used rarely as a site for bone harvesting. Usually they are used for reconstruction of long bones with defects or for in spine surgeries. The vascularized fibula can also be used for

TABLE III
OVERVIEW OF THE AVERAGE OF BONE VOLUME HARVESTED FROM THE AIC AND THE PIC

Study	Bone volume AIC	Bone volume PIC
Ahlmann et al. 2002 [20]	54.53 ml	55.12 ml
Burk Del Valle et al. 2016 [15]	26.29 ml	33.82 ml
Engelstad et al. 2010 [21]	10.4 ml (+/- 4.16 ml)	12.0 ml(+/- 3.43 ml)
Gerresen et al. 2008 [22]	9.15 ml	not assesed
Hall et al. 1991 [23]	12.87 ml (+/- 5.23 ml)	30.31 ml (+/- 3.42 ml)
Kessler et al. 2004 [24]	9 cm (range,5-12 cm)	25.5 cm (range, 17-29 cm)
Marx et al. 1988 [25]	72 ml	88 ml
Nikolopoulos et al. 200 [26]	17.63 ml (range, 4.98-33.57 ml)	not assessed

reconstruction of limbs, infected nonunions in long bones, femoral head osteonecrosis, nonunions of femoral neck or for the treatment of pseudoarthrosis in the tibia [31].Fibular graft harvesting brings potential complications along , such as neurovascular injury, ankle instability, compartement syndrome, neurovascular injury and weakness muscles. In the proximal third peroneal nerves and muscle branches are the primary risk. Peronel vessels in the middle third are a potential risk when harvesting bone from the fibula. The distal 10 cm of the fibula should stay intact, as it will cause instability in the ankle. The ideal harvesting area of the fibula is the middle third. The distal and the proximal 10 cm should be avoided, because of the risk to damage nerve and cause ankle instability [31].

Tuncay et al. [32] conducted a retrospective study were 20 patients underwent revision hip arthroplasty with the use of cortical autograft of the fibula. The author recommends to use a cortical autograft from the fibula for reconstruction of femoral defects. The advantage of the fibular autograft compared to a stut allograft is the cost-effective, easy to harvest, no risk of viral transmission. Although, cortical allografts are larger, longer and have a thicker cortices than the fibular autograft. The median defect length of the fibular autograft group was 7 cm (range, 1-10 cm) and the median graft length was 16.5 cm (range, 10-30 cm).

4) Bone graft harvesting form the calcaneus: The calcaneus is beside the iliac crest, the tibia or the greater trochanter of the femur a good option for regional harvesting of autologous bone graft for foot and ankle surgeries. The advantage of the calcaneus as donor site for such surgeries is the low morbidity, minimal incision, easy accessibility and use of regional block anaesthesia. For this harvesting option in most of the cases no major complications were reported. Pathological fractures, haematoma formation or infections are rare and most of the patients have no pain, no numbness at the operation site and no nerve injuries. The calcaneus as a graft can be used to treat arthrodesis or to conduct modified Lapidus procedure or osteotomies [33], [34], [35].

In a cohort study, conducted by Khademi et al. [34] fifty patients from March 2015 till March 2018 underwent midfoot or forefoot surgeries with use of autogenous bone graft harvested form the calcaneus. For harvesting the autogenous bone the lateral wall of the calcaneal body was broken and the bone material was scooped out with a curette. The maximal volume of harvested graft form the calcaneal body can be up to 9 ml. For most oft he foot and ankle surgeries this volume is sufficient. IN case more volume is needed the combination with other substitutes, such as hydroxyatite ceramic is possible to increase the volume. Thus, bone graft from the calcaneus is an easy and safe procedure for ankle and foot surgeries. The calcaneus is able to regenerate quickly after the bone harvest procedure.

Baumhauer et al. [33] studied 130 patients, that had surgeries, involving autograft harvesting from the iliac crest, distal tibia, proximal tibia or the calcaneus. Twenty patients underwent surgeries with use of calcaneal bone graft. The amount of harvested graft was 1-3 ml for nine patients, 4-6 ml for six patients and 7-9 ml for 5 patients. The author notes the chance for significant heel pain for patients with calcaneal graft is one in five.

Raikin [35] harvested calcaneal graft from 44 patients. The graft was used for tarsometatarsal arthrodesis, repair of metatarsal nonunion, revision of metatarsophalangeal arthrodesis, ankle arthrodesis, repair of navicular fractures , Lapidus bunionectomy, repair of fibular nonunion and for bone graft and curettage of bone cysts in the foot or ankle. For most of the patients 5 to 10 ml bone graft material were harvested. Only two patients reported persistent numbness and the satisfaction rate with the calcaneal bone graft procedures was 100%.

5) Bone graft harvesting form the Olecranon: Harvesting autogenous bone form the proximal ulna has the advantage to be able to avoid potential morbidity associated with the need of a second surgical site or use of general anesthetic. Cortical and cancellous bone can be harvested trough a proximal cortical window (PCW) or a dorsal cortical widow (DCW), where the second one is the traditionally method. It has been reported, that several fractures occurred after harvesting olecranon bone graft trough a dorsal cortical window. Also complications such as bursitis, triceps tendonitis and ulnar nerve injuries may occur. The amount of bone that can be harvested from the olecranon is limited but in most of the hand and wrist procedures sufficient [36].

Anderson et al. [36] compared the strength of the harvested ulna bone and the volume between the different approaches. They found a mean volume for packed bone harvested trough DWC and PCW was 2.1 ml (range, 1.4-3.5 ml) and 2.2 ml (range, 1.7-3.0 ml), respectively. The amount to be harvested trough the different approaches is similar and has no significant difference. As well for the strength of the ulnar bone there was no significant difference found.

Bruno et al. [37] carried out a quantitative analysis on the volume of cancellous bone available from the olecranon, the iliac crest and the distal radius. They reported a mean volume of 2.8 ml (+/- 0.7 ml) for packed cancellous graft harvested from the olecranon. The bone was harvested trough a 1cm hole with the use of straight or curved curettes. They also mentioned in the report, that the gender has been significant for the packed bone volume. Approximately 50% more bone volume was harvested from the male subjects than from the female. The authors suggest the olecranon as a good alternative bone graft donor to the distal radius for upper extremity surgeries, especially in the case when the distal radius is not available. However, the amount of bone to be harvested from the olecranon is limited. If larger volumes are required the iliac crest can provide twice the amount of cancellous bone and is therefore recommended to pack larger defects.

Babushkina and Edwards [38] described a technique of harvesting corticocancellouse bone from the olecranon. They described the olecranon as a good bone graft source for corticocancellos bone .The ratio of cancellous to cortical bone in the olecranon is much larger and therefore a suitable donor site for small bones with need of structural support such as metacarpals. The olecranon offers a larger volume of graft that can be obtained compared to the available amount of the distal radius The authors treated a defect of 2.5 cm successfully with corticocancellous bone of the olecranon.

Chim et al. [39] recommend using olecranon grafts for the treatment of scaphoid fractures, reconstruction of small to medium defects in the metarcarpales or phalanges, especially when a wedge graft or cortical strut graft is required. From the olecranon a good corticocancellous bone block can be harvested. They mention, that the olecranon as graft donor is not recommended for patients above 50 years, because there is only little cancellous bone to harvest available. In this study a block of 5 mm x 10 mm was obtained for scaphoid bone grafting, although it is possible to harvest blocks up to 20 mm x 30 mm, depending on the individual size of the olecranon.

6) Bone graft harvesting form the radius: The distal radius is often forgotten as a potential donor site. Thereby, the distal radius provides a good source of bone graft for hand and wrist surgeries. The advantage of the distal radius compared to the iliac crest is, that only one surgical site is needed This decreases the patient morbidity, costs and increases the recovery time for patients. The amount of cancellous bone graft available from the distal radius is less than form the iliac crest but in most cases sufficient for most hand surgeries and reconstructions. A cadaveric adult distal radius can offer 2.4 ml of cancellous bone [40].

Bruno and colleagues quantified the volume of cancellous bone available in the distal radius on sixteen cadaveric specimens. The harvesting of the bone of the distal radius was performed trough a window created with a 1cm dowel. A mean volume of packed bone of 2.7 cm^3 (+/- 0.9) was obtained from this window. The created defect was filled with silicone polymer.

McGrath and Watson [41] reported harvesting bone from distal radius in 76 patient. In 60 patients, cortical bone grafts up to 3 x 1 cm were harvested. In 19 cases bone was harvested from the proximal ulna with an average field of 2 cm x 8 mm. The biggest cortical bone graft harvested from the ulna was 4.5 cm x 1 cm large. These grafts were used for bone lengthening or for tumor, osteotomy arthrodesis or nonunion treatment. Grafts were also obtained from the phalanges. The volumes of the estimated grafts were not further described.

Matson et al. [42] evaluated the volume and density of cancellous bone of the distal radius based on computed tomographic scans of the wrist of 33 patients. The average volume in the distal regions of the radius measures 0.82 cm^3 compared to 0.27 cm^3 in the proximal region of the radius. The greatest volume was found distal-central with 1.20 cm^3 followed by distal-ulnar region with 0.81 cm^3. The distal-central bone is therefore more voluminous than other regions.

Horne et al. [43] demonstrated in a cadaveric biomechanical study that harvesting too much of cancellous bone may increase the risk of fracture. They recommend to harvest less than 25% of the available metaphyseal cancellous bone.

IV. Discussion

A. 3D data acquisition and volume estimation

In this work, the possibility of measuring the volume of various bone segments and bone structures using a navigation system was tested. The digitization process turned out to be relatively simple and quick to perform. Depending on the volume size, an average of 1-5min was required for digitization. The conventional way of volume determination is volume calculation using a CT scan [44]. The volume of the desired area is calculated based on the segmentation data of the scan. This method has the advantage that it is quite accurate. However, performing a CT scan requires ionizing radiation, which is harmful to humans. Therefore, if this method is used intraoperatively with the help of a C-arm, all personnel in the operating room and the patient are exposed to radiation. Additionally, the segmentation of the CT scan requires quite some time. The variant of volume determination with the help of a navigation system does not require harmful radiation and can therefore be considered a safe and gentle alternative to CT volume determination [45], [46]. For this reason, the possibility of digitizing and calculating the volume of bone in the intraoperative area can be of great benefit to the surgeon. A navigation system is, in any case, indispensable during a surgical procedure and is therefore always available. With this process of volume calculation, the surgeon receives volume information about the desired bone part in the fastest and safest way.

Putzer et al. [47] described the accuracy of this measurement procedure in a study in which acetabulum were digitized using a navigation system for the volume determination and compared their volumes with CT measurements and theoretically calculated volumes. The volume estimation could be performed with a 5% error rate within 1-4 min. The author recommends the procedure for implant selection and for the selection of structural allografts to fill the acetabulum.

Of course, this could also be beneficial for many other surgeries using autografts or allografts. Digitization can be performed quickly, depending on the sampling rate, and provides immediate results to the surgeon. Thus, this procedure could be particularly worthwhile if volume determination would be required within an operation. The procedure could be particularly helpful when filling bone defects caused by tumors. In this way, the volume of the bone can be determined before the tumor is removed. After the tumor has been removed, the volume can be measured again and the bone defect volume can be calculated from the negative and the necessary amount of autograft can be estimated.

Furthermore, this method of volume determination can also be helpful for 3D printing of implants. For 3D printing of implants and scaffolds it is important to know the volume, shape and dimensions. Bones could be digitized in a simple way, their surface and volume calculated and printed directly [48].

Difficulties in digitizing the bones were mainly the smooth guidance of the pointer. The bones used in this work had a clean and quite smooth surface. It was often difficult to guide the pointer without slipping on the smooth surface. Extreme caution is required when guiding the pointer, especially on edges. Too fast movements led to the pointer slipping and air points were generated. Guiding the pointer can also prove difficult when changing structures, such as from porous to smooth surfaces. On large regular surfaces, the implementation is quite simple and the pointer can be guided quickly. Another difficulty was that the pointer must always be within sight of the navigation system's camera. However, the program does not give any warning signal if the pointer leaves the field of view. Thus, it can often happen that the pointer is covered by something or loses visual contact to the camera and it is not noticed. Scanning the bone with the pointer requires high concentration. Although the status of the pointer changes to red when it loses line of sight, this is not noticeable to the user who is concentrating fully on the bone. For this reason, it would be helpful if the system would alert the user with an acoustic signal in case the pointer loses visual contact to the camera. With practice and training, the pointer is easier to lead and a faster and more error-free scanning is possible. In a real intraoperative situation, the method of digitization may also encounter obstacles. The area to be scanned may be restricted by adjacent bones. If a bone is therefore not free enough, it could occur the problem that not enough points can be acquired.

B. *Maximal volume of bone grafts*

The iliac crest is the graft which can provide the largest amount of cancellous or corticocancellous bone graft volume. The largest amount of harvested graft found in literature is 88 ml cancellous bone material obtained from the posterior iliac crest [25]. Studies described the acetabular reamer technique where larger volumes up to 90 ml can be obtained [49], [50]. All studies included in this work show that the largest amount of bone volume can be harvested from the posterior iliac crest. Harvesting bone graft from the anterior iliac crest is limited due to the potential risk to harm ligaments or muscles [20], [17]. Ahlmann et al. [20] reported, that the volume which can be harvested averages 30 ml from the posterior iliac crest and 13 ml from the anterior iliac crest. Burk et al. [15] marked an average volume of 34 ml of uncompressed bone and 25 ml of compressed bone from the posterior iliac crest. The author found that 26% of the uncompressed bone is blood or fat and therefore not useful for bone grafting. Therefore the iliac crest is an excellent graft for large bone defects, which requires cancellous or corticocancellous bone graft. For interventions where a smaller amount of bone graft is required it is recommended to take bone graft form a local area to avoid a second operation site.

The second largest amount of bone graft can be obtained form the tibia. The largest amount harvested form the tibia found in the literature is 70 ml of cancellous bone [27]. The average of harvested cancellous bone ranges from 11.3 ml to 38 ml. Most of the investigated studies mark an average of 25 ml cancellous bone [27], [14], [30], [28]. However, harvesting large amounts of cancellous bone from the tibia carries the risk to cause postoperative fractures or instability of the bone [29], [30], [14]. Therefore if more than 40 ml cancellous graft is needed the iliac crest is the better choice [30]. The tibia is an important weight bearing part of the knee joint and therefore harvesting cortical bone graft is not recommended. Harvesting autogenous cancellous bone form the tibia shows low complication rates. It is best suited for foot and ankle surgeries as the field of operation can kept to a local area and for most of the foot and ankle surgeries the tibia provides enough graft volume [27], [14]. The calcaneus is a good choice for regional harvesting of autologous bone graft in foot and ankle surgeries. The calcaneus is able to regenerate quickly and the harvesting procedure is quite easy and safe to conduct [33], [34], [35]. The maximal bone graft volume harvested from the calcaneus is 10 ml of cancellous bone reported by Raikin [35]. The other authors harvested a maximum amount of 9 ml form the calcaneus [34], [33].This might be enough for most of the foot or ankle surgeries, such as repair of metatarsal nonunion, revision of arthrodesis, and repair of small fractures of the foot. The studies remark that harvesting cancellous graft from the calcaneus has the advantage of minimal incision, low morbidity and the possibility to use a regional block anaesthesia for the whole operation process [33], [34], [35]. Based on the results of the included studies the calcaneus is a good suited donor site for ankle and foot surgeries with >10 ml graft volume needed.

For harvesting autologous graft from the fibula the studies provide information about the obtained graft length but not about volume sizes of the graft [31], [32]. From the fibula only cortical graft can be obtained. Therefore it is a good choice for reconstructive surgeries of long bones or wherever structural support is needed [31], [32]. Harvesting cortical graft from the fibula can cause severe complications such as ankle instability, nerve or muscle injuries or compartment syndrome [31]. Therefore, the harvesting process is strict and only the middle third can be obtained, that limits the graft size to a range from 10cm to 30cm, with a recommended length of 10 cm [32]. Therefore, the fibular autograft is only a good choice when a small graft >20 cm is needed [32].

For larger defects, a stut allograft may be the better choice. Both studies recommend the use of fibular autograft for the reconstruction of femoral defects [31], [32]. Furthermore Tuncay et al describes advantages of the fibular autograft compared to a allograft as cost-effective, easy to harvest and no viral transmission risk [32].

For upper extremity surgeries the olecranon is a good suited donor site. The advantage is no need of a second surgical site or general anaesthetics, which decreases the potential morbidity. From the olecranon cortical and cancellous bone can be harvested. The volume described in the study of Anderson et al. [36] and Bruno et al. [37] deviate only slightly. Based on the results of these studies the maximal amount of packed cancellous bone graft to be harvest is 3.5 ml. The study of Bruno et al. [37] demonstrates a correlation between the gender and the maximal harvested graft volume, where approximately 50% more graft volume can be obtained from the male subjects. In none of the other reviewed literature was found similar evidence. Chim et al.[39] mentions, that from subjects older than 50 years only little amount of cancellous bone can be harvested and is therefore not recommended. The authors harvested blocks up to 20 mm x 30 mm from the olecranon. All studies indicate that the amount of graft size is individual and depending from bone quality and individual size of the olecranon.
Another potential donor site for upper extremity surgeries is the radius. The advantage, same as for the olecranon is that only one surgical site is needed and only local anaesthetic is needed. Therefore using the olecranon or the radius as donor site for hand and wrist surgeries decreases the patient morbidity, costs and increases the recovery time for the patients. However, the maximum volume of harvested bone from the radius varies in the studies included. Bruno et al. [37] obtained the greatest volume with 3.6 ml from the distal radius while Matson et al obtained only 1.20 ml from the distal-central radius. Patel et al. [40] agrees with the Bruno et al. and marks a maximal volume of cancellous bone of 2.4 ml. McGrath and Watson [41] was the only study which reported the use of the distal radius for cortical bone grafts with a size up to 3 cm x 1 cm. The olecranon provides a larger amount of cortical bone to be harvest with up to 4.5 cm x 1 cm or 2 cm x 3 cm depending on the individual. The main risk of harvesting cancellous bone graft from the olecranon are postoperative fractures, therefore the volume is limited and is recommended to be less than 25% of the available cancellous bone of the olecranon. Horne et al. [43] obtained bone grafts from specimens with an average of 80 years, therefore the compressive strength of the specimens may be diminished and altered the results. As Chim et al. [39] mentioned that harvesting graft from the olecranon from patients above 50 years the quantity and quality is not the best anymore. These results indicate, that harvesting bone graft from the olecranon or distal radius a greater volume can be obtained from younger patients. As these donor sites do not provide a great amount of bone to be harvested it is not recommended for large defects. For patients above 50 years it should be taken into account that the graft volume might not be as large as expected. No further evidence was found in the literature that mentions age as a factor for decreased quantity and quality of bone grafts from the fibula, tibia, calcaneus, or iliac crest.

Acknowledgment

The authors would like to thank the department of Experimental Orthopedics for providing the required devices and for the support.

References

[1] T. T. Roberts and A. J. Rosenbaum, "healing Bone grafts , bone substitutes and orthobiologics The bridge between basic science and clinical advancements in fracture healing," *Organogenesis*, vol. 6278, p. 12, 2012.
[2] A. R. Gazdag, J. M. Lane, D. Glaser, and R. A. Forster, "Alternatives to Autogenous Bone Graft: Efficacy and Indications," *Journal of the American Academy of Orthopaedic Surgeons*, vol. 3, no. 1, pp. 1–8, 1995.
[3] V. Campana, G. Milano, E. Pagano, M. Barba, C. Cicione, G. Salonna, W. Lattanzi, and G. Logroscino, "Bone substitutes in orthopaedic surgery : from basic science to clinical practice," *Journal of Materials Science: Materials in Medicine*, pp. 2445–2461, 2014.
[4] W. Wang and K. W. K. Yeung, "Bioactive Materials Bone grafts and biomaterials substitutes for bone defect repair: A review," *Bioactive Materials*, vol. 2, no. 4, pp. 224–247, 2017.
[5] A. H. Schmidt, "Autologous bone graft: Is it still the gold standard?" *Injury*, vol. 52, pp. S18–S22, 2021.
[6] M. Kamal, F. Gremse, S. Rosenhain, A. K. Bartella, F. Ho, and P. Kessler, "Comparison of Bone Grafts From Various Donor Sites in Human Bone Specimens," *The Journal of Craniofacial Surgery*, vol. 00, no. 00, pp. 1–5, 2018.
[7] V. M. Goldberg and S. Akhavan, "Biology of Bone Grafts," pp. 57–65, 2005.
[8] M. Zileli, E. C. Benzel, and G. R. Bell, "Chapter 93 - bone graft harvesting," in *Spine Surgery (Third Edition)*, third edition ed., E. C. BENZEL, Ed. Philadelphia: Churchill Livingstone, 2005, pp. 1253–1261.
[9] S. H. Khan SN, Cammisa FP Jr, "The Biology of Bone Grafting," pp. 77–86, 2005.
[10] W. P. Bae DS, "Free Vascularized Fibula Grafting: Principles, Techniques, and Applications in Pediatric Orthopaedics." *Orthopaedic Journal at Harvard Medical School*, pp. 77–86, 2006.
[11] R. Elfring, M. de la Fuente, and K. Radermacher, "Assessment of optical localizer accuracy for computer aided surgery systems," *Computer Aided Surgery*, vol. 15, no. 1-3, pp. 1–12, 2010, pMID: 20233129. [Online]. Available: https://doi.org/10.3109/10929081003647239
[12] M. Klemm, "Intraoperative Planning and Execution of Arbitrary Orthopedic Interventions Using Handheld Robotics and Augmented Reality," Ph.D. dissertation, 2018.
[13] R. Dimitriou, E. Tsiridis, and P. V. Giannoudis, "Current concepts of molecular aspects of bone healing," pp. 1392–1404, 2005.
[14] C. Myeroff and M. Archdeacon, "Autogenous Bone Graft : Donor Sites and Techniques," *The Journal Bone and Joint Surgery*, vol. 93, pp. 2227–2236, 2011.
[15] T. Burk, J. Del Valle, R. A. Finn, and C. Phillips, "Maximum quantity of bone available for harvest from the anterior iliac crest, posterior iliac crest, and proximal tibia using a standardized surgical approach: A cadaveric study," *Journal of Oral and Maxillofacial Surgery*, vol. 74, no. 12, pp. 2532–2548, 2016.
[16] K. Singh, F. M. Phillips, E. Kuo, and M. Campbell, "A prospective, randomized, double-blind study of the efficacy of postoperative continuous local anesthetic infusion at the iliac crest bone graft site after posterior spinal arthrodesis: A minimum of 4-year follow-up," *Spine*, vol. 32, no. 25, pp. 2790–2796, 2007.
[17] F. Finocchiaro and Æ. D. A. Fabris, "Comparison of single-level L4-L5 versus L5-S1 lumbar disc replacement : Results and prognostic factors Comparison of single-level L4 – L5 versus L5 – S1 lumbar disc replacement : results and prognostic factors," *European Spine Journal*, no. May 2014, 2009.
[18] A. Wolfe and H. K. Kawamoto, "the Iliac-Bone Graft," *The Journal Bone and Joint Surgery*, no. 411, p. 978, 1978.

[19] T. Boucree, Ã. D. Mclaughlin, S. Akrawe, V. Darian, and A. Siddiqui, "Posterior Iliac Crest Bone Graft : How Much Is Enough ?" *The Journal of Craniofacial Surgery*, vol. 28, no. 8, pp. 2162–2164, 2017.

[20] E. Ahlmann, M. Patzakis, N. Roidid, L. Shepherd, and P. Holtom, "Comparison of Anterior and Posterior Iliac Crest Bone Grafts in Terms of Harvest-Site Morbidity and Functional Outcomes," *THE JOURNAL OF BONE AND JOINT SURGERY*, vol. 84, no. 5, pp. 716–720, 2002.

[21] M. E. Engelstad and T. Morse, "Anterior Iliac Crest , Posterior Iliac Crest , and Proximal Tibia Donor Sites : A Comparison of Cancellous Bone Volumes in Fresh Cadavers," *J Oral Maxillofac Surg.*, vol. 68, no. 12, pp. 3015–3021, 2010.

[22] M. Gerressen, A. Prescher, D. Riediger, D. van der Ven, and A. Ghassemi, "Tibial versus iliac bone grafts : a comparative examination in 15 freshly preserved adult cadavers," *Clin. Oral Impl. Res.*, vol. 19, pp. 1270–1275, 2008.

[23] M. B. Hall, W. P. Vallerand, D. Thompson, and G. Hartley, "Comparative Anatomic Study of Anterior and Posterior Iliac Crests as Donor Sites," *J Oral Maxillofac Surg.*, vol. 49, pp. 560–563, 1991.

[24] P. Kessler, M. Thorwarth, E. Nkenke, and F. W. Neukam, "Harvesting of bone from the iliac crest —– comparison of the anterior and posterior sites," *Journal of Oral Maxillofacial Surgery*, vol. 43, pp. 51–56, 2005.

[25] R. E. Marx and M. J. Morales, "Morbidity from Bone Harvest in Major Jaw Reconstruction: A Randomized Trial Comparing the Lateral Anterior and Posterior Approaches to the Ilium," *Journal of Oral Maxillofacial Surgery*, vol. 48, pp. 196–203, 1988.

[26] C. E. Nikolopoulos, A. F. Mavrogenis, G. Petrocheilou, C. Kokkinis, P. Diamantopoulos, and P. J. Papagelopoulos, "A three-dimensional medical imaging model for quantitative assessment of proximal tibia vs . anterior iliac crest cancellous bone," *Clinical Orthopaedics and Related Research*, vol. 15, pp. 233–237, 2008.

[27] R. Dalal, H. Sugathan Kovilazhikathu, and R. Racha, "Proximal Medial Tibial Bone Graft Harvesting in Foot and Ankle Surgery," *The Journal of Foot and Ankle Surgery*, vol. 2, no. June, pp. 27–30, 2015.

[28] A. S. Herford and B. J. King, "Medial Approach for Tibial Bone Graft : Anatomic Study and Clinical Technique," *Journal of Oral Maxillofac Surg. Oral Maxillofacial Surgery*, vol. 61, no. 3, pp. 358–363, 2003.

[29] V. Alt, P.-j. Meeder, and D. Seligson, "The Proximal Tibia Metaphysis : A Reliable Donor Site for Bone Grafting ?" *Clinical Orthopaedics and Related Research*, vol. 414, pp. 315–321, 2003.

[30] G. A. Catone, B. L. Reimer, D. McNeir, and R. Ray, "Tibial autogenous cancellous bone as an alternative donor site in maxillofacial surgery: A preliminary report," *Journal of Oral and Maxillofacial Surgery*, vol. 50, no. 12, pp. 1258–1263, 1992.

[31] N. A. Ebraheim, H. Elgafy, and R. Xu, "Bone-Graft Harvesting From Iliac and Fibular Donor Sites : Techniques and Complications," *Journal of the American Academy of Orthopaedic Surgeons*, vol. 9, no. 3, pp. 210–218, 2001.

[32] Tuncay, R. Tözün, O. Aliyev, G. Dikmen, G. Uzer, and V. E. Özden, "Onlay fibula autografting technique and its comparison with cortical allograft for the reconstruction of periprosthetic bone defects around the femur," *International Orthopaedics*, no. 45, pp. 71–81, 2020.

[33] J. Baumhauer, M. S. Pinzur, R. Donahue, W. Beasley, and C. DiGiovanni, "Site selection and pain outcome after autologous bone graft harvest," *Foot & Ankle International*, vol. 35, no. 2, pp. 104–107, 2014, pMID: 24227683.

[34] F. Khademi, A. Erfani, M. A. Erfani, and A. R. Vosoughi, "Bone graft harvesting from the calcaneus using lateral wall corticotomy technique by an osteotome," *Foot & Ankle Specialist*, vol. 0, no. 0, p. 1938640020916269, 2020, pMID: 32326754.

[35] S. M. Raikin and K. Brislin, "Local bone graft harvested from the distal tibia or calcaneus for surgery of the foot and ankle," *Foot & Ankle International*, vol. 26, no. 6, pp. 449–453, 2005, pMID: 15960910.

[36] M. C. Anderson, A. C. M. Chong, G. L. Lucas, P. J. Czuwala, and P. H. Wooley, "Harvesting Bone Graft From the Olecranon: A Quantitative and Biomechanical Comparison of Proximal and Dorsal Cortical Windows," *The American Journal of Orthopedics®*, no. July, pp. 321–324, 2014.

[37] R. J. Bruno, M. S. Cohen, A. Berzins, and D. R. Sumner, "Bone Graft Harvesting From the Distal Radius , Olecranon , and Iliac Crest : A Quantitative Analysis," *The Journal of Hand Surgery*, vol. 26A, no. 1, pp. 135–141, 2001.

[38] A. Babushkina and S. Edwards, "Corticocancellous olecranon autograft for metacarpal defect reconstruction: A case report," *HAND*, vol. 7, no. 4, pp. 457–460, 2012, pMID: 24294172.

[39] H. Chim, F. Malkoc, S.-C. Tay, A. Yam, and L.-C. Teoh, "Technique of olecranon bone grafting for surgical fixation of scaphoid fractures," *The Journal of Hand Surgery*, vol. 36, no. 7, pp. 1220–1223, 2011.

[40] J. C. Patel, N. Haven, K. Watson, E. Joseph, J. Garcia, R. Wollstein, and N. Haven, "Long-Term Complications of Distal Radius Bone Grafts," *The Journal of Hand Surgery*, pp. 784–788, 2003.

[41] M. H. Mcgrath, H. K. Watson, and N. Haven, "Late results with local bone graft donor sites in hand surgery," *Journal of Hand Surgery*, vol. 6, no. 3, pp. 234–237, 1981.

[42] A. P. Matson, A. E. Federer, E. M. Meisel, S. R. Barchick, D. S. Ruch, and M. J. Richard, "Determination of the optimal location for bone graft harvest in the distal radius," *HAND*, vol. 15, no. 6, pp. 863–869, 2020, pMID: 30829063.

[43] L. T. Horne, P. M. Murray, S. Saha, and K. Sidhar, "Effects of Distal Radius Bone Graft Harvest on the Axial Compressive Strength of the Radius," *YJHSU*, vol. 35, no. 2, pp. 262–266, 2009.

[44] I. Kodikara, D. Gamage, I. Abeysekara, and I. Ilayperuma, "Impact of volume calculation formulae on volume estimation accuracy of different shaped objects: an in vitro ultrasound and ct study," *Acta Radiologica*, vol. 61, no. 10, pp. 1414–1420, 2020, pMID: 32013542.

[45] S. P. Raman, M. Mahesh, R. V. Blasko, and E. K. Fishman, "CT scan parameters and radiation dose: Practical advice for radiologists," *Journal of the American College of Radiology*, vol. 10, no. 11, pp. 840–846, 2013.

[46] R. A. Hayda, R. Y. Hsu, J. Mason DePasse, and J. A. Gil, "Radiation exposure and health risks for orthopaedic surgeons," *Journal of the American Academy of Orthopaedic Surgeons*, vol. 26, no. 8, pp. 268–277, 2018.

[47] D. Putzer, F. Scholl, L. Dankl, D. Dammerer, M. Thaler, and M. Nogler, "Intraoperative bone defect measurement in the acetabulum using a navigation system: The influence of bone porosity on the digitalization process," *Medical Engineering Physics*, vol. 59, pp. 75–80, 2018.

[48] A. Haleem, M. Javaid, R. H. Khan, and R. Suman, "3D printing applications in bone tissue engineering," *Journal of Clinical Orthopaedics and Trauma*, vol. 11, pp. S118–S124, 2020.

[49] G. Westrich, D. Geller, M. O'Malley, J. Deland, and D. Helfet, "Anterior iliac crest bone graft harvesting using the corticocancellous reamer system," *Journal of orthopaedic trauma*, vol. 15, no. 7, p. 500—506, 2001.

[50] S. C. Brawley and R. B. Simpson, "Results of an alternative autogenous iliac crest bone graft harvest method," *Orthopedics*, vol. 29, no. 4, April 2006.

Franziska Kofler is master student at the MCI Innsbruck/Austria in Medical Technologies. She graduated with a bachelor's degree in radiology technology in Innsbruck 2019.