# A Prototype Tool for the Selection of Femur Head Bone Donations for manufacturing Customised Allografts

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***Abstract*—An increase in hip revision surgery is projected to be caused by aging society and decreasing age at initial total hip arthroscopy. Over 2 million bone graft procedures are performed per year worldwide, whereas 34% of all interventions are conducted during hip revision surgery. This development results in an imbalance between the supply and demand of allografts. A prototype software tool for surface reconstruction and the selection of a fitting femoral head bone donation for the manufacturing of customized allografts was developed. Using the open-source library Open3D a Python script was implemented. Surface reconstruction of an allograft point cloud was performed using different reconstruction methods. A three stage bone donation selection procedure was implemented. The implemented script was applied to two different shaped allograft point clouds. Surface reconstruction and the selection of fitting femoral head bone donations were conducted. From 10 femoral heads, the procedure considered 5 for a cylindrical shaped and 9 for a wedge-shaped allograft as suitable. The prototype fulfills the requirements, however, further improvement steps have been identified.**

***Index Terms*—bone graft, allograft, femoral head, Open3D.**

## I. Introduction

### A. Bone Grafting

THE procedure of bone grafting aims to repair diseased or damaged bone structures by transplanting mostly autologous or allogeneic bones. With 100 years of successful clinical use and over 2 million bone graft procedures performed per year worldwide, it can be considered as well known and established. Bone is the second most common tissue transplanted in the U.S., although tremendous research efforts are expedited to develop artificial bone graft substitutes.[1] [2] [3]

Bone grafts are classified into autografts, allografts, xenografts and synthetic grafts. Autografts are taken from the host directly. Allografs are taken from a genetically similar donor. Xenografts are taken from a genetically dissimilar donor. Synthetic grafts are created with an artificial bone substitute material. The properties of autogenous bone graft are considered as the gold standard for bone grafting. To evaluate the efficacy of allografts and bone graft substitutes, they are compared against the known results of the usage of autografts. Autografts are osteogenic, histocompatible, have no risk of transmitting diseases and provide mechanical stability. The major drawback of autogenous bone graft is its limited supply. Allograft is the most used bone substitute in Europe and about 800 000 allografts are implanted in the U.S. each year. The sources of allografts include living donors (femoral head of patients undergoing a total hip arthroscopy), multi-organ donors ,and post-mortem donors. [2] [3] [4] [5]

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### B. Femoral Head Allografts and Revision Hip Arthroplasty

In Europe, the most common method of supplying allografts is internal hospital bone banks. The primary harvest source of femoral heads is primary hip arthroplasty. Although a projection by Kurtz et al identifies a higher demand of primary total hip arthroplasties, femoral head allografts is an increasingly rare resource that should not be wasted. The analysis of the donor, bone graft procurement and processing is extensive and costly but necessary to minimize the risk of infection and ensure contaminate-free allograft. However, this process often results in the exclusion of a potential donor, creating a limited supply for femoral head allografts. According to Abbas et al only 5% of potential femoral heads were harvested during hip arthroplasty. The estimation of required bone graft is often inaccurate preoperatively. This results in an additional challenge to avoid bone graft wastage. The quality of bone graft differs as the head size and density variate. Hand morselization with large bone nibblers is considered the traditional approach for preparing the allograft whereas the method of bone milling may be more efficient. [6] [7] [8] [9]

Driven by the aging population and the younger age of patients receiving primary hip arthroplasty, an increase of revision arthroplasties can be observed. An increased need for bone grafts and substitutes leads to a higher quantity of allografts available over recent years, but the demand is still higher than the supply. Previously the main application for bone allografts was spinal fusion surgery. Now the majority of bone graft is used for reconstructing bone defects during revision hip arthroplasty (34% of all bone allografts) and for fracture surgery (24% of all bone allografts). Especially the need of a large amount of bone allograft in revision arthroplasties is considered as a major factor for creating an imbalance between demand and supply of bone allografts.[4] [9]

### C. Aim

The thesis aims to develop a prototype software tool that generates a three-dimensional view of an allograft based on a point cloud and determines geometric properties of the structure. The analyzed structure is compared against several femoral head bone donations to identify a fitting donation for manufacturing the desired shaped allograft. The proposed tool is aiming to increase the efficiency of allograft usage within bone reconstruction procedures to minimize bone graft wastage.

## II. Methods

To acquire data for the software program two point cloud measurements of possible allograft structures were performed. A Stryker eNlite Navigation System (Stryker Corporation, Michigan, USA) with a standard ball tip was used for measurement. For the first allograft a cylindrical shape was chosen and 1385 data points were measured. For the second allograft a wedge-shaped shape was chosen and 565 data points were measured.

As no point cloud data of femoral heads was available, ten spheres with diameters in the range of 42mm to 60mm were generated. Each sphere was converted into a point cloud of 500 data points to simulate different femoral heads.

For development, the IDE Visual Studio Code (Version 1.57.1. Microsoft Corporation, Washington, USA) and Python (Version 3.8. Python Software Foundation, Oregon, USA) were used. The open-source array programming library NumPy [10] was used for array computation.

### A. Open3D

Zhou et al have been developed the open-source library Open3D since 2015. It aims to support the rapid development of software that deals with 3D data for C++ and Python. Open3D follows two primary design principles: the usefulness implementation of popular representations, algorithms and platforms ,and an ease-of-use approach. Open3D distinguishes between three different representations: point clouds, meshes ,and RGB-D images. For each representation basic and widely used algorithms such as sampling, visualization and normal estimation are implemented. To guarantee easy and fast compilation heavyweight libraries are excluded and lightweight dependencies are selected. As replacement for the heavyweight but powerful libraries, light-weight alternatives (e.g., pybind11 instead of Boost.Python) or in-house implementations are used. This aims for the approach of keeping the library as simple as possible. [11]

### B. Surface Reconstruction

The input of the developed software tool is a point cloud of an allograft. To generate a dense 3D geometry, surface reconstruction methods are performed. This leads to a first view of the actual shape of the allograft. In Open3D three different methods of surface reconstruction are implemented.

*1) Alpha Shapes:* Alpha Shapes is an approach to define and compute the shape of a finite point set in three-dimensional Euclidean space. Edelsbrunner and Mücke describe the concept of alpha shapes: "Let *S* be a finite set in $R^3$ and $\alpha$ a real number with $0 \leq \alpha \leq \infty$. The $\alpha$-shape of *S* is a polytope that is neither necessarily convex nor necessarily connected. For $\alpha = \infty$, the $\alpha$-shape is identical to the convex hull of *S*. However, as $\alpha$ decreases, the $\alpha$-shape shrinks by gradually developing cavities. These cavities may join to form tunnels, and even holes may appear." [12]

Intuitively, the polytope containing the points of *S* is hollowed out by a sphere with the radius $\alpha$, whereas $\alpha$ must be chosen that the sphere does not enclose any of the points of *S*. To simplify the concept of alpha shapes $R^3$ can be seen as space filled with styrofoam and the points of *S* can be seen as rocks. A spherical eraser with the radius $\alpha$ is omnipresent in this space and carves out styrofoam at all positions where it is not enclosing any of the rocks. The resulting carved-out object is called $\alpha$-hull. The surface of the $\alpha$-hull is straightened by substituting straight edges for circular ones and triangles for spherical caps. The resulting object is the $\alpha$-shape of *S*. The $\alpha$-shape can be concave and disconnected and some of its components can be as small as single points. [12]

Besides the reconstruction of objects which have been sampled by points, alpha shapes find applications in fields such as pattern recognition and cluster analysis. The alpha-shapes approach in surface reconstruction faces some limitations. First, a standard $\alpha$-shape can not distinguish between surface points and points marking the edge of the interstice, resulting in the coverage of the interstice. Second, if the surfaces of two separate objects are near to each other, the $\alpha$-shape includes triangles, that connect points of both objects. Third, $\alpha$-shapes improperly connect the adjacent surfaces of sharp turns or joints, resulting in a "webbed-foot" appearance. [13] [14]

*2) Ball-Pivoting Algorithm:* The Ball-Pivoting Algorithm (BPA) aims to find a triangle mesh that interpolates an unorganized set of points. The method defined two requirements for the samples: the samples are distributed over the entire surface and that an estimate of the surface normal is available for each measured sample. The main concept of the BPA is closely related to the alpha-shapes approach. Let *S* be a finite set of points in $R^3$ describing the surface of a three-dimensional object. For now, *S* is dense enough that a ball with the radius $\rho$ cannot pass through the surface without touching points of *S*. We start by placing the ball in contact with three points of *S*. We "pivot" the ball sustaining contact with two of the three initial points until the ball touches another point. All triplets of points that are contacted by the ball form new triangles resulting in a set of triangles. This set constitutes the interpolating mesh of the three-dimensional object. The BPA is considered efficient in terms of execution time and storage requirements. Furthermore, it proved to be robust enough to deal with the noise in real scanned 3D data. [15]

*3) Poisson Surface Reconstruction:* The Poisson surface reconstruction method aims to generate a watertight 3D mesh of a given point cloud. As input point clouds with oriented normal are required. The gradient of the defined indicator function is equated to a vector field. the vector field is built from the point cloud normal vectors. The resulting Poisson equation is solved and the reconstructed surface is generated by using the marching cubes algorithm. [16] [17]

## III. Results

A Python script that generates a 3D view of an allograft and selects a fitting bone donation for manufacturing a customized allograft was implemented. The input file of the script must be a point cloud of the desired allograft. The output of the script is all bone donations that can be used for manufacturing the desired allograft. The best-fitting donation is recommended by the script to the user. The user can select which donation is displayed together with the desired allograft. In the final view the user can apply manual translations to the allograft if needed.

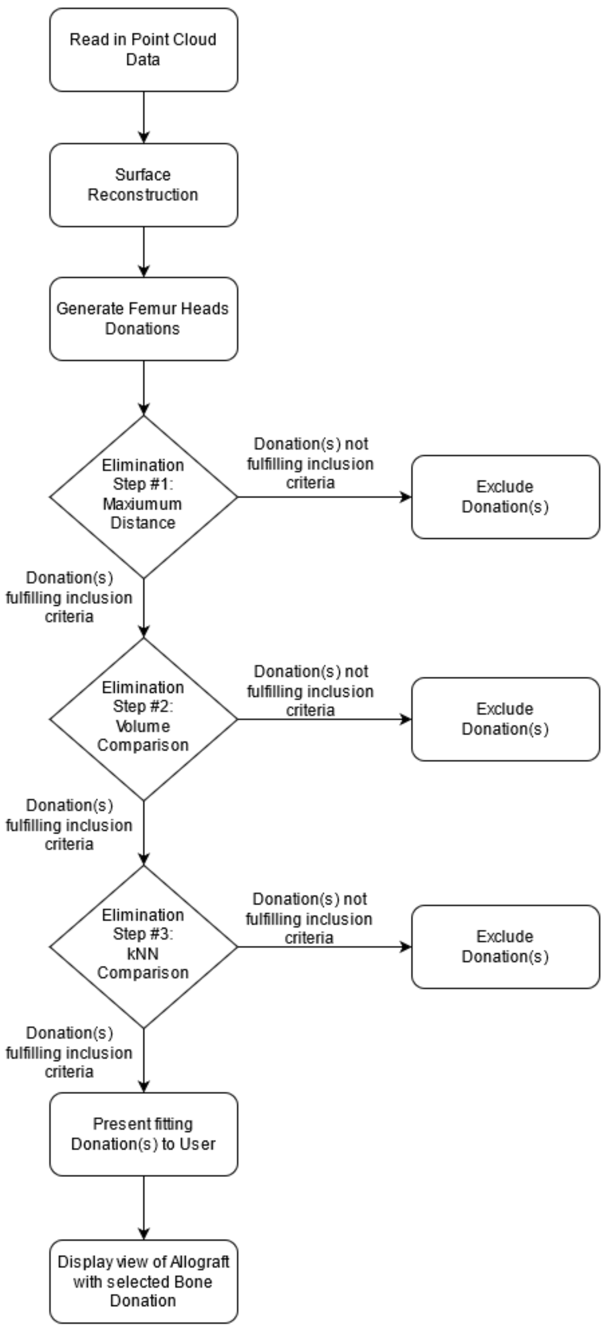


Fig. 1. The structure of the Python Script is shown using a flowchart.

*1) Surface Reconstruction:* Three different approaches for the surface reconstruction of an allograft point cloud were implemented: Alpha Shapes, BPA and Poisson surface reconstruction. Each reconstruction method was applied to both, the cylindrical and the wedge-shaped allograft point cloud.
The Alpha Shapes surface reconstruction method was applied to both allografts using $\alpha$ values of 20mm, 14.5mm, 10.5mm, 10mm, 7.6mm, 5.5m and 4mm for the cylindrical allograft and 15mm, 11.5mm, 10mm, 8.8mm, 6.8mm, 5.2mm and 4mm for the wedge-shaped allograft. The reconstructed surfaces using the alpha shapes approach and the Poisson surface reconstruction method can be found in Appendix A.
For surface reconstruction of the cylindrical allograft using the BPA, radii of 4mm, 7mm, 10mm and 13mm were chosen. Figure 2 shows the reconstructed surface of the cylindrical allograft applying the BPA method.

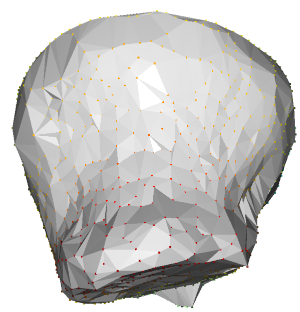

Fig. 2. The Surface Reconstruction of the cylindrical allograft using the BPA approach is shown. The point clouds of the allograft is shown additionally.

The BPA surface reconstruction method was applied on the wedge-shaped allograft using radii of 2mm, 4mm, 6mm and 8mm . Figure 3 shows the reconstructed surface of the wedge-shaped allograft applying the BPA method.

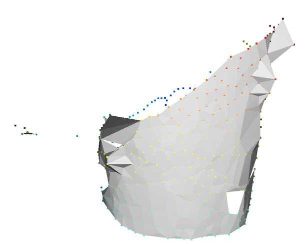

Fig. 3. The Surface Reconstruction of the wedge-shaped allograft using the BPA approach is shown. The point clouds of the allograft is shown additionally.

*2) Femoral Head Bone Donation Selection:* A donation selection procedure to identify fitting femoral head bone donations for the desired allograft was implemented. Due to unavailability of real femur head bone donation point cloud data, 10 femur head bone donations were simulated. The Triangle meshs of ten spheres with diameters of 42mm, 44mm, 46mm, 48mm, 50mm,52mm, 54mm, 56mm, 58mm and 60mm and their point clouds were generated. The spherical properties of the substitutes simulate the geometrical properties of real femoral head bone donations. The implemented bone donation selection was applied to the cylindrical and the wedge-shaped allograft point clouds.

The first step compare the maximal distance between two allograft data points to the maximal distance between two bone donation data points data points. If the allograft distance is larger than the bone donation distance, the bone donation is excluded. In the second step the volume of the allograft is determined and compared to the volumes of the remaining bone donations. If the volume of the allograft exceeds the volume of the bone donation the bone donation is excluded. For the final elimination translations were applied to the allograft and bone donation point clouds aiming to get the same shared origin. 5 randomly chosen points of the allograft point cloud are selected and referred to as 'anchor points'. For each anchor point the 30 nearest points of the bone donation point clouds are identified. The distance from the anchor point and its 30 nearest points to the shared origin is determined. If the distance of the anchor point to the origin is larger than one of the distances of the 30 nearest points, the bone donation is excluded.

For the manufacturing of the cylindrical allograft 5 out of 10 bone donations are considered suitable. The bone donations with diameters of 52mm, 54mm, 56mm, 58mm and 60mm passed each elimination step. At the first elimination step 5 donations were excluded. At the second and third elimination step no donation was excluded. 9 out of 10 bone donations are considered suitable for the manufacturing of the wedge-shaped allograft. The bone donations with diameters of 44mm, 46mm, 48mm, 50mm, 52mm, 54mm, 56mm, 58mm and 60mm passed each elimination step. 1 bone donation was excluded at the first elimination step. At the second and third elimination step no donation was excluded. The smallest fitting femoral head bone donation is considered as best fit and is recommended by the script to the user. Figures 4 and 5 show the allograft point clouds (red) and the associated best fitting bone donation point cloud.

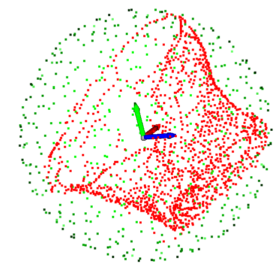

Fig. 4. The point clouds of the cylindrical allograft (red) and the best fitting femur head bone donation (green) with a diameter of 52mm (green) are shown.

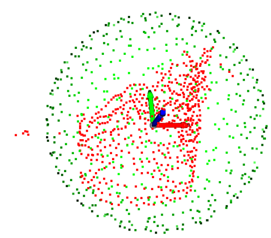

Fig. 5. The point clouds of the cylindrical allograft (red) and the best fitting femur head bone donation (green) with a diameter of 44mm (green) are shown.

## IV. Discussion

The aim of the surface reconstruction is to provide a first impression of the allograft shape to the user. Therefore the outcome which was aimed for is characterised through simplicity and fast computation time. A basic accuracy must is required but on a superficial level. However, considering a surface reconstruction as sufficient is heavily depending on the subjective view of the user. Broad objective criteria, such as that the surface is watertight can be defined but the evaluation of surface reconstruction is on a subjective level.

The alpha shapes reconstruction provides a solid first impression of the cylindrical and the wedge-shaped allograft. However, there is no objective way to identify the best fitting $\alpha$. This is done using a trial-and-error approach. For the examined allografts $\alpha = 10mm$ is considered the most suitable value. Outliner data points of the wedge-shaped allograft point clouds are included in the surface reconstruction resulting in two extra 'pikes'.

The BPA surface reconstruction presented is more robust against outliners compared to the alpha shapes approach and is considered fast and efficient. Publications such as Wang et al [18] compare their approach to the BPA in terms of computation time and efficiency. Maiti and Chakravarty [17] conclude that the quality of the surface reconstruction depends heavily on the ball radius, the clustering radius and the angle threshold. For the aim of this thesis the BPA approach is considered as the best fitting surface reconstruction method.

The Poisson surface reconstruction is considered as not fitting for the needs of this thesis caused by the long computation time and the insufficient result compared to the other methods.

The first two elimination steps of the implemented bone doantion selection procedure focus on the geometrical properties of the bone donations and the allografts. Outliner data points may falsify the result. The outliners observed in the wedge-shaped allograft point cloud do not impact the result as the point cloud is small compared to the bone donations. Therefore boundary cases must be defined and tested.

In the second elimination step, the volume of the allograft is compared with the volumes of the bone donations.

The final elimination step uses a randomly picked anchor point of the allograft point cloud, identifies the 30 nearest points of the bone donation and compares the distance of each point to the shared origin of the point clouds. As the real femoral head bone donations are simulated by spheres the determination of the radius of the sphere would be sufficient. This step aims to assess the geometrical irregularities of natural femoral heads. If the point clouds of natural femoral heads are used a random selection of the anchor points is not expedient.

To increase the procedure's reliability following tasks were defined: usage of point clouds of real femoral heads as bone donations, change random selection of anchor points to manual selection of points of interests, elimination of outliner data points, definition of standardised procedure for data acquisition and execution of tests with boundary cases.

## V. Conclusion

The aim defined for this thesis was achieved by the implementation of a prototype surface reconstruction and bone selection procedure. As the implemented solution is in the prototype state, certain limitations and corresponding mitigation for the development of the procedure have been identified.

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## Appendix A
## Surface Reconstruction using Alpha Shapes and Poisson method

Fig. 6. The Surface Reconstruction of the cylindrical allograft using the Alpha Shapes with $\alpha = 10mm$ approach is shown.

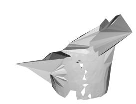

Fig. 7. The Surface Reconstruction of the wedge-shaped allograft using the Alpha Shapes with $\alpha = 10mm$ approach is shown.

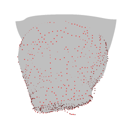

Fig. 8. The Surface Reconstruction of the cylindrical allograft using the Poisson surface reconstruction method is shown.

Fig. 9. The Surface Reconstruction of the wedge-shaped allograft using the Poisson surface reconstruction method is shown.