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Measuring bone defects for acetabular revision surgery for choosing an appropriate reconstruction strategy: A concept study on plastic models

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ABSTRACT

Background: Bone defects can be filled with autografts, allografts and artificial bone-materials. The aim of this study was to evaluate whether the digitization of known defect models with a navigation system is a reliable measurement method for estimating the size of a bone defect.

Methods: Six preformed, cylindrical and cone-shaped defects on an artificial hip-bone were digitalized by six different observers. Reference volumes were gathered by measuring the depth of the defects, using an alginate impression material to fill out the defects and calculating the volumes from a CT scan.

Results: One out of the six preformed defects showed a statistically significant difference between the digitalization and the calculation, four showed a significant difference between the digitalization and the mould as well as between the digitalization and the CT calculation.

Conclusions: This technique offers satisfactory results and consistent reproducibility when digitalizing big defects with relatively simple shape. Decreasing size and increasing complexity of the defects leads to more imprecise measurements.

1. Introduction

Bone defects often have a multifactorial genesis. Especially when removing bone tumors, in cranio-maxillofacial interventions and in revision total hip arthroplasties bone defects can be generated, that subsequently might require treatment. Bone grafting is a surgical technique to fill up bone defects by replacing it with autogenous, allogenous or artificial bone-material [1–3].

Autografts are being used because of their osteoinductive nature, their histocompatibility and the lack of transmission risks for viral or bacterial disease [2]. Disadvantages include the limited quality or quantity of disposable bone, high rates of donor-site morbidity and associated blood-loss [1].

Allografts are extracted from donors and then either deep-fried, irradiated or fresh-frozen. The advantages of this technique are missing donor-side co-morbidities and good availability if bone banks are present [4]. Disadvantages are the immune response on the recipient-side, missing osteoinductive properties and the risk of infections [1,2]. Testing methods for viral or bacterial diseases have improved greatly since the introduction of allografts and the last documented transmission of a viral disease dates back to the year 2000 [5].

Ceramics, mostly hydroxyapatite (HA), tricalcium phosphate (TCP) and calcium sulfate, or bioglass are often used as artificial bone-material [1,2,6]. They show no associated infection risks and are available in large quantities. Because of their brittle composition ceramics must be shielded from sheer forces until osteointegration takes place [1,2]. Because allografts lack osteoinductive properties, mixing them with bone-marrow cells introducing growth factors may be beneficial [7]. Alternatively, allogeneous bone can be mixed with HA and TCP. Studies with a mean follow-up of 1.5 and 2 years show promising clinical results and little complications using this method [8]. It has been possible to prove bone-ingrowth in an animal model, both histologically and via μCT [9,10].

Besides structural allografts, impaction bone grafting is a technique to fill up bone defects with bone chips [11]. To provide perfect conditions for impaction bone grafting, the size of the bone chips should be

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evenly distributed [12]. Chips with a size of 8 mm–10 mm have a positive influence on the stability of the implant [13–15].

Washing and defatting also increases the initial stability [13–16]. Studies using micro-CT showed that a pore-size over 150 µm induced a significantly higher bone ingrowth [13,17]. Because the force used to impact the bone chips varies a lot, authors suggest using an ex vivo compaction device [13] or a pneumatic hammer [18]. Impaction bone grafting can be used to fill small to medium-sized defects even in young patients [19]. By using a metal mesh as a lateral containment, even bigger defects can be filled [13,20]. Marshall et al. recommended an efficient use of the limited number of femoral head allografts on hand [21].

The quantity of allografts necessary to fill up the bone defect is usually not known intraoperatively. The aim of this study was to evaluate whether the digitization of known defect models with the aid of a navigation system is a reliable measurement method for estimating the size of the bone defect.

2. Materials and methods

Three geometrical objects, one hemisphere and two cylinders closed on one side respectively, with known volume were digitalized. The hemisphere (HS) had a diameter of 7 mm and a height of 2.40 mm, with a resulting volume of 48.86 mm^3. The first cylinder (C1) had a diameter of 22 mm and a height of 17 mm. The resulting volume was 6.46 cm^3. The second cylinder (C2) had a diameter of 20 mm and a height of 41.50 mm and therefore a volume of 13.04 cm^3. Each geometrical element was digitized 10 times and the volume was calculated from the registered point-cloud. The digitized volumes were compared to the mathematically obtained reference value.

Subsequently, one artificial hip-bone with 6 preformed, cylindrical and cone-shaped defects (Sawbones number 1318, Pacific Research Laboratories Inc., Vashon Island, USA) was used and the 6 defects of the same specimen were digitalized 10 times by 6 different observers (Fig. 1). The volume was calculated using the gathered point-cloud and compared to reference volumes. Firstly, the reference volumes were determined by measuring the depth and the diameter of the defect five consecutive times and calculating the volume. Out of the calculated five volumes the mean volume was used as a reference. Secondly the defects 1–5 were poured out with alginate impression material (Henry Schein, Melville, NY, USA) following the instructions of the company. After hardening, the cast material was submerged into water and the volume was measured using the Archimedes principle. The mould-filling method could not be used for defect 6 because it had openings on both sides. For each defect, five moulds were created by filling up the cavities.

For digitalization and gathering the point clouds, a Stryker eNlite Navigation System (Stryker Corporation, Kalamazoo, Michigan, USA) was used (Mean trueness values of 0.058 mm with standard deviation 0.033 mm [22]). A new tracking software was developed using MITK and OpenIGTLink open source toolkits [23]. The software is a generic, intraoperative and image-free planning and execution application for arbitrary orthopedic interventions with a robotic device [24].

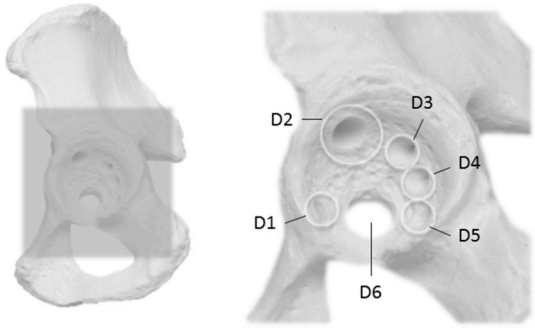

Fig. 1. A Sawbone Model Nr. 1318 with 6 acetabular defects with different sizes are shown. The defect volumes were measured using a digitizer, a filling mould and by calculation of the volume out of 5 consecutive depth measurement and compared to a CT scan.

The inner surface of the bodies was swept up to the top edge with the tip of the pointer-tool (pointer tip diameter 1.5 mm) recording a point cloud. The point cloud was imported into MATLAB (MATLAB, version R2014a, MathWorks, Natick, Massachusetts, USA) and embedded into a x-y-z coordinate system. The volume was then calculated using Delaunay triangulation.

For comparison a CT scan was performed before and after reaming to calculate the reamed volume. CT scans were obtained with a "Light Speed VTC" scanner (GE Medical Systems, Great Britain) in helical mode using a peak voltage of 100 kV, a tube current of 320 mA, a slice distance of 0.625 mm, a data collection diameter of 500 mm, a data reconstruction diameter of 165 mm and an image resolution of 512 × 512.

Radiographic volume of the defects was assessed on a 3D image processing workstation (AW 4.6, General Electric, Milwaukee, WI, USA) by three experienced radiologists.

Data collection was done in Excel (Excel 2013, Microsoft Corporation, Redmond, Washington, USA). Graphs were created using *Prism* (Prism 6 for Windows, version 6.05, GraphPad Software Inc.,La Jolla, Kalifornien, USA). Statistical analysis was performed using *SPSS* (IBM SPSS Statistics, version 22.0.0.0, IBM Corporation, Armonk, New York, USA).

Outliers were defined as values that exceeded 100% and fell below 10% of the median. These values were removed from the data set. The amount of single points recorded was evaluated using MATLAB. 4 vol, which consisted of less than 20 individual points, were removed from the data set.

A One-Sample Kolmogorov-Smirnov test was performed on the volume-values gathered from digitalizing the two cylinders and the hemisphere with known volume to test for normal distribution. To compare the digitalized to the calculated values, a One-Sample T-Test was performed for the volumes with known size.

A One-Sample Kolmogorov-Smirnov test was performed on the data volume-values gathered from digitalizing the preformed defects to test for normal distribution. After that, an Independent-Samples Kruskal-Wallis test was performed for each defect to compare the digitalized volume to the measured volumes. As defect 6 was a cylindrical defect with two open areas, it was not possible to create a representative mould. Therefore, due to the difficulties concerning the creation of a mould, the digitalization and the calculation from the depth measurements were compared using the nonparametric Kolmogorov Smirnov Test for independent samples.

Lastly, Intraclass correlation coefficient (ICC) was calculated for the digitalization (6 observers) and CT measurements (3 observers).

3. Results

Digitizing a known object (HS, C1 and C2) resulted in an underestimation of the calculated volume by 31.4% for HS, 1.0% for C1, and 3.2% for C2 compared to the real volume (Fig. 2).

The distribution of HS was normal with a mean of 0.03 cm^3 and a standard deviation of 0.01 cm^3 (18.8% of the mean; $p > 0.05$). The measurement of C1′s volume was normal with a mean of 6.39 cm^3 and a standard deviation of 0.15 cm^3 (2.3% of the mean, $p > 0.05$).

C2′s volume was normally distributed with a mean of 12.62 cm^3 and a standard deviation of 0.59 cm^3 (4.8% of the mean, $p > 0.05$).

Digitalizing the HS, a statistically significant lower volume was measured ($p < 0.005$) with a mean difference of 0.02 cm^3. C1 showed a statistically significant lower digitized volume (mean difference of 0.06 cm^3) than the calculated volume ($p < 0.005$). C2 showed a statistically significant lower digitized volume (mean difference of

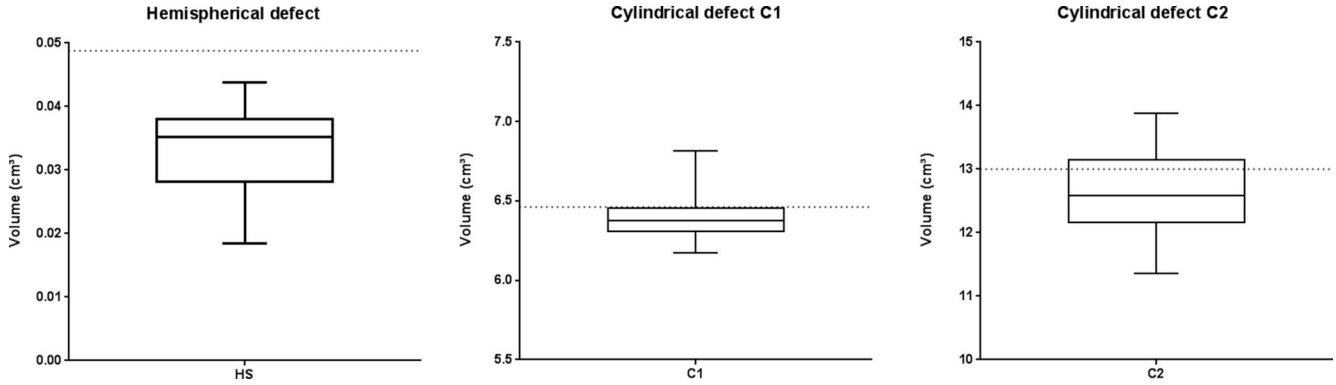

Fig. 2. Box blots showing minimum and maximum (bars) and median and interquartile range (box) of the digitized volume of the three volumes with known size. The dotted line shows the calculated reference volume.

0.38 cm^3) than the calculated volume ($p < 0.005$).

After digitizing the pre-made defects in the acetabulum, we removed 6 outliers in defect 1, 3 outliers in defect 2, 2 outliers in defect 3 and 4, 6 outliers in defect 5 and 5 outliers in defect 6. Volumes of defect 1 and 4 showed normal distribution, while defect 2, 3, 5 and 6 were not normally distributed ($p > 0.05$).

In defect 1 a statistically significant higher mean value was found for digitized volumes in comparison to the volume calculated from depth measurements ($p = 0.006$) (Fig. 3). The digitized volume was statistically significantly lower than the mould ($p < 0.001$). The difference between mould measurement and the calculated volumes from depth measurement was statistically significantly different ($p < 0.001$). There was no significant difference between the CT-measurement and digitalization as well as the mould, however, a significant difference between the CT-measurements in comparison to the calculation could be found ($p = 0.017$).

In defect 2 a significant difference was observed between the CT-measurement and the digitalization ($p = 0.003$) as well as the mould

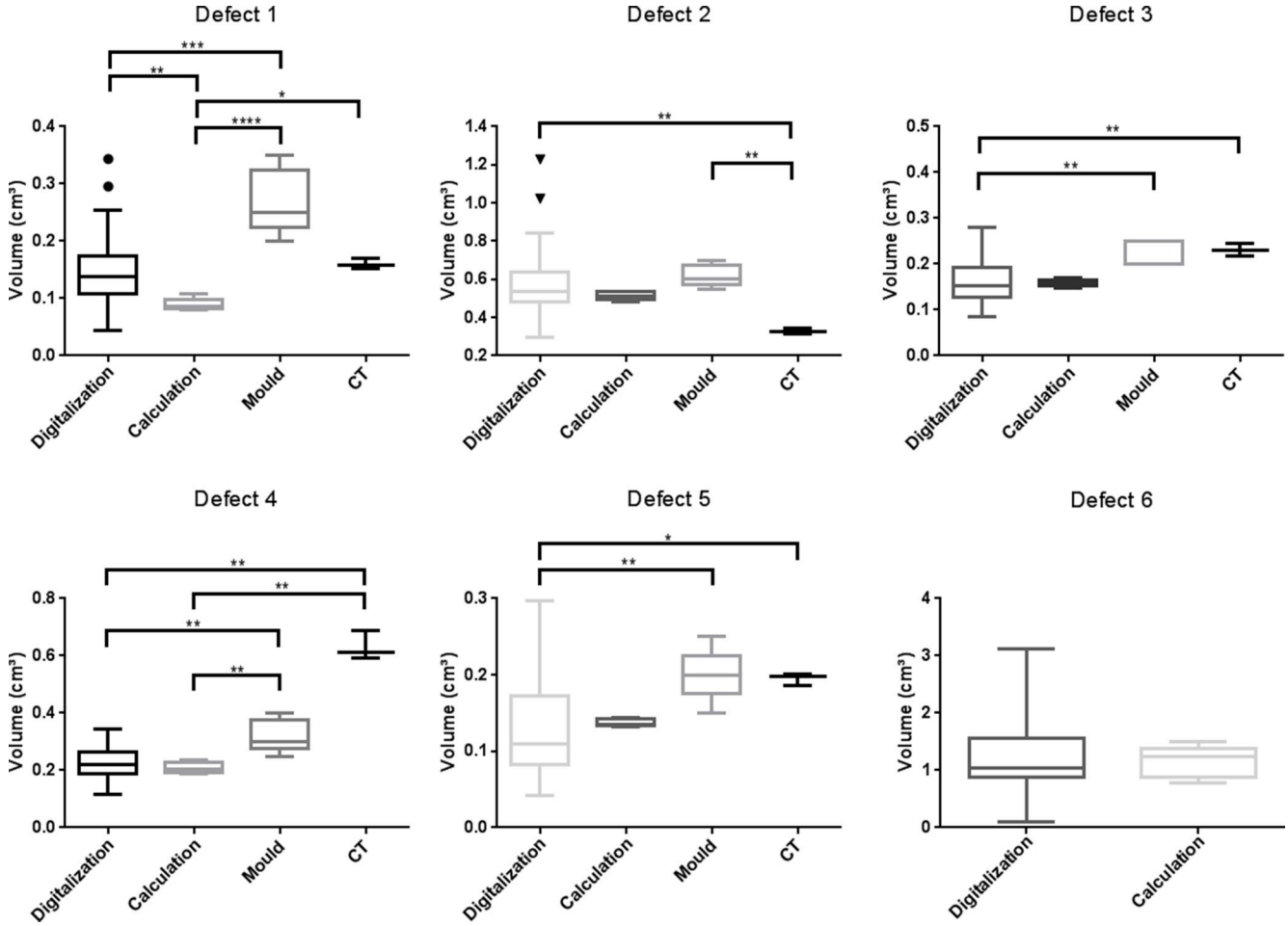

Fig. 3. Results for the four measurement methods are shown for the 6 different acetabular defects as box blots (bars are showing minimum and maximum values and the box the median and interquartile range). 1–6 shows the result of an Independent-Samples Kruskal-Wallis Test. In defect 1–5 the digitalization, the moulds and the calculation were compared. In defect 6, due to the difficulties concerning the mould, the digitalization and the calculation were compared. A star above the bracket connecting two groups indicates a significant difference between the compared groups ($P < 0.05$).

Table 1
Mean and standard deviation are reported for each defect and for each measurement in cm^3. Differences between digitalization (1) and all other methods are reported if statistical significance level was reached ($p < 0.05$). NS indicates that no statistical difference was found between the two measurement methods.

	Digitalization (1)	Calculation (2)	Mould (3)	CT (4)	(1–2)	(1–3)	(1–4)
Defect 1	0.14 (0.05)	0.09 (0.01)	0.27 (0.06)	0.16 (0.01)	0.05	−0,13	NS
Defect 2	0.57 (0.13)	0.51 (0.02)	0.62 (0.06)	0.33 (0.02)	NS	NS	0.24
Defect 3	0.16 (0.04)	0.16 (0.01)	0.22 (0.03)	0.23 (0.01)	NS	−0.06	−0.07
Defect 4	0.23 (0.05)	0.21 (0.02)	0.32 (0.06)	0.63 (0.05)	NS	−0.09	−0.41
Defect 5	0.13 (0.06)	0.14 (0.01)	0.20 (0.04)	0.20 (0.01)	NS	−0.07	−0.07
Defect 6	1.18 (0.43)	1.15 (0.28)			NS		

($p = 0.001$) (Fig. 3). The other differences were not significant. In defect 3 no statistically significant differences could be found between the digitalization procedure and the calculation method. A significantly higher volume was observed in defect 3 ($p = 0.004$, 4 ($p = 0.002$) and 5 ($p = 0.005$) for the mould procedure when compared to the digitalized volume (Fig. 3). A statistically significant difference could be found between mould and calculation method ($p = 0.009$) for defect 4, while for defect 3 ($p = 0.066$) and 5 ($p = 0.147$) no statistically significant difference could be found. When comparing the CT-measurement to the digitalization, a significant difference was found in defect 3 ($p = 0.007$), 4 ($p = 0.003$) and 5 ($p = 0.035$) CT-measurement and calculation only showed a significant difference in defect 4 ($p = 0.005$). For defect 6, it was not possible to obtain a mould as well as a CT-measurement because the defect was passing through the acetabulum and therefore had two openings (Fig. 3). Table 1 shows mean and standard deviation for each method and the difference from the digitalization to all other method if statistically significant.

In Table 2, mean and standard deviation for the digitalized volumes of the six defects measured by the 6 individual observers are reported. ICC calculation showed a good consistency and reproducibility of digitalization and CT measurements made by different observers while measuring the defects. The estimation of the reliability of single ratings was above 0.8 for both methods, while the estimation of the reliability of average ratings was above 0.9 (Table 3).

4. Discussion

The method for digitalizing bone defects shows reproducible results when surveying bigger volumes. The digitalized volumes gathered from hemispherical and cylindrical geometrical objects were underestimating the calculated volume. Standard deviations of 2.3% up to 4.8% of the mean were observed for the cylindrical objects, while in the small hemisphere standard deviation varied by 18.8%.

This might be a result of the digitalizer's head size, which leads to an underestimation of the volumes. Furthermore, it turned out to be difficult to move the pointer tool exactly along the upper rim of the objects. A tendency to slip outwards and therefore artificially increase the calculated volume could be observed. It has been difficult to control this phenomenon. However, this effect might be decreased in severity by repetition and training. Our data does not show a decrease of this systematic error. In our case, the volumes got more and more complex with the increasing number of digitalizations, and volumes with a high level of complexity are prone to inaccuracy. These findings are consistent with a previous study that found no significant difference between digitalized and calculated volumes in big defects [25].

As we evaluated the preformed defects, we find standard deviations ranging from 22.4% up to 43.4% of the mean for all observers combined. This may sound like a lot, but one has to keep in mind that the defects were very small (only 0.2 cm^3 up to 1 cm^3). Air-points, which tend to enlarge the digitalized volume, have a much more severe impact on the digitalization if the volume is smaller.

When comparing the ICC of the digitalization to the ICC obtained from the CT measurements, both correlations are over 0.80 which means that they are consistent reproducible within different observers.

To our knowledge, there is no intra-operative method to calculate the size of bone defects. Only CT-based techniques, which deduce the size of a bone defect by measuring the extent of an osteolytic zone, are described in the literature [26]. Authors also report an automated three-dimensional reconstruction and measurement of bone defects caused by tooth extraction using Cone-Beam Computed Tomography. Assisted by image processing software, they showed accurate results and good interobserver reproducibility in their studies [27,28]. Our CT measurements were significantly higher in almost all cases when compared to the digitalized volumes. This may be due to segmentation issues. It could be unpractical to apply CT scans for measuring bone defects in an operative setting, as the size of the bone defect may change, or the bone defect is primarily created during the operation (for example due to the revision of a cup). Therefore, the new volume can only be guessed. The method tested in this article can be used intraoperatively by combining a camera-based navigation system, like the ones used in knee surgery, with measurement software. This would allow to gather point clouds and measure the volume of bone defects in an intraoperative setting without using X-Rays.

A possible application for the technique would be measuring the volume of a bone defect in order to determine the exact amount of bone chips needed to fill up that defect. Putzer et al. and Albert et al. showed that, after a 12-s compaction with a hammer, bone chips have a density of ~0.37 g/cm^3 [18,29]. By using this technique, the voids in the allograft material were closed. A higher compaction energy will lead to higher density values by destroying the trabecular structure of the allografts, which is not the aim of impaction bone grafting. Considering the maximum density, which can be obtained with manual impaction, and knowing the defect volume, the amount of bone chips needed to fill up a bone defect can be estimated. The maximum density may be more reproducible when controlling the grain size distribution of the allografts and the impaction process itself [12,29] as well as material

Table 2
Mean and standard deviation (in brackets) for each observer and for the 6 different digitized defects. Volumes are reported in cm^3.

Observer	Defect 1	Defect 2	Defect 3	Defect 4	Defect 5	Defect 6
1	0.10 (0.02)	0.48 (0.07)	0.14 (0.03)	0.21 (0.03)	0.09 (0.01)	0.95 (0.09)
2	0.19 (0.04)	0.57 (0.11)	0.15 (0.04)	0.18 (0.04)	0.08 (0.03)	0.92 (0.19)
3	0.14 (0.03)	0.58 (0.07)	0.20 (0.03)	0.27 (0.03)	0.16 (0.03)	1.74 (0.22)
4	0.14 (0.04)	0.51 (0.05)	0.13 (0.02)	0.21 (0.03)	0.09 (0.02)	1.04 (0.18)
5	0.13 (0.05)	0.53 (0.15)	0.14 (0.03)	0.20 (0.05)	0.14 (0.07)	0.86 (0.35)
6	0.16 (0.04)	0.73 (0.12)	0.20 (0.02)	0.28 (0.03)	0.20 (0.02)	1.62 (0.40)

Table 3
Intraclass correlation coefficient is reported for the digitalized volumes obtained by 6 different observers each carrying out 30 measurements (outliers were not considered) on the 5 different defects. Volume measurements of the 5 different defects resulting from a CT scan were carried out by 3 different experienced radiologists and shown as a comparison. 95% Confidence interval is reported in brackets.

	Number of raters	Number of subjects	ICC Single measures	ICC Average measures
Digitalization	6	158	0.81 (0.77–0.86)	0.96 (0.95–0.97)
CT	3	5	0.99 (0.95–0.99)	0.99 (0.98–0.99)

properties as far as possible [15,16,30]. When calculating the amount of allografts necessary, it has to be taken into account that the volume is being reduced by approximately 30% due to the impaction process [12]. Differences in graft density will be obtained with different impaction forces applied [29]. By implementing a volume calculation into clinical practice, the dosage of allografts could be planned more efficiently, and shortages or waste of donor material could be avoided. In case of shortages, other filling substances can be added to the allografts [6].

Calculating the volume of the defect may also be helpful for selecting donor material from a database to produce a well-seated structural allograft. Future developments of robotically assisted orthopedic surgery might include the possibility for creating perfectly shaped structural allografts, which fit into the intraoperatively digitalized volume. To achieve this, the calculated three-dimensional bodies could be transferred to a CNC milling machine or a 3D-printer, and a fitting implant could be generated (i.e. from artificial bone-materials). Also, the data gathered could be used to select the best-fitting metal augment or revision prosthesis for each individual defect. Additionally, the defect could just be visualized on a screen to help the surgeon shape a well-fitting graft.

A limitation to this trial is that gaining a reference-volume in the acetabular defects turned out to be difficult, as irregular boarders were present. Therefore, the reference volumes calculated by measuring the depth of the defects are an approximation. A similar problem was encountered when pouring out the defects with the moulding material. Small amounts of residual material might have remained in the defects, which may have altered the measured volume. Thus the reference measurements are also affected by inaccuracies.

Another limitation of the set-up was, that only convex defects (conical, cylindrical e.g.) can be measured. This may have caused some of the inaccuracies during the registration process of the point cloud and also represents a major drawback. In a future application this has to be addressed via creating virtually closed defects by estimating a closed surface on the defect. This might be possible by either considering the shape and position of the final implant, or by estimating the anatomy using statistical models.

In addition, the software we used had some limitations in its possibilities. For example, there was no option to delete points. Either software filtering algorithms that detect air-points, or hardware that does not allow air-points to be registered in the first place, could improve the results, especially in small defects. Although the measurements may be affected by inaccuracy, and volume calculation algorithms have to optimized, we believe that this method is precise enough for estimating the right amount of allografts needed to fill up the defect. Calculating the quantity of bone material needed for filling up the bone defect could be even more important if autografts from the same patient are used. If allografts act as an antibiotic carrier, it might be even more helpful to know the volume of the defect for quantifying the effective dose of antibiotics [31].

Defects digitalized in the study were relatively small in regard to bone defects typically seen in revision surgery (~50–~100 cm^3). A more detailed analysis of the defect sizes should be evaluated in a retrospective analysis of patient cases, if CT scans were performed. In future research, the measurement method should be evaluated on custom made defect models (e.g. 3d printed models of patient data). Also, the quantity of impacted bone allografts needed for filling such defects should be evaluated by using the estimated values from the measurement method described in this article. Finally, the compaction process itself should also be evaluated by using a micro-CT scan, studying the effect of compaction on the trabecular structure of the allografts.

Defect 6 was an open defect, where bone impaction techniques typically will not be applied without the usage of a metal mesh or other techniques for creating a closed defect.

Lastly, it must be acknowledged that using a navigational setup for the sole purpose of digitalizing a bone defect could be unpractical. In a setting with severe bone loss however, a surgeon might be willing to using a navigation system aimed at simplifying the operation. In this case, calculating the size of a bone defect can easily be done additionally. This could pose a helpful tool to decide on further treatment.

5. Conclusion

In conclusion, the aim of this study was to evaluate whether the digitization of known defect models with a navigation system is a reliable measurement method for estimating the size of bone defects. This technique showed good results and good reproducibility when digitalizing bigger defects with a relatively simple shape. Increasing complexity of the defects, however, lead to more imprecise measurements. When the defects are smaller, differences between the observers is likely be due to registration of air-points. In an intraoperative setting, smaller defects may not be a concerning problem, because the volume of small defects can easily be estimated by the surgeon. By knowing the influencing factors on the density during the impaction process it is possible to calculate the bone filling material necessary [15,29,30]. Potential applications for this measurement setup could be calculating of the exact amount of bone chips needed to fill a bone defect. Furthermore, it could assist the surgeon in picking the best-fitting augmentation method for large structural defects. With the help of a intraoperative, easy to use, surgical CAD application custom made bone transplants can be produced using robotic assisted surgery [24].

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.compbiomed.2019.103336.

Author contributions statement

All authors have seen and concur with the contents of the manuscript. All authors have made substantial contributions and were involved in the study as well as the preparation of the manuscript.

The authors declare that the material within the submitted paper has not been and will not be submitted for publication elsewhere, including electronically in the same form, in English or in any other language, without the written consent of the copyright-holder.

Compliance with ethical standards

This article does not contain any studies with human participants or animals performed by any of the authors.

References

[1] A.R. Gazdag, J.M. Lane, D. Glaser, R.A. Forster, Alternatives to autogenous bone graft: efficacy and indications, J. Am. Acad. Orthop. Surg. 3 (1) (1995) 1–8.

[2] S.C. Gamradt, J.R. Lieberman, Bone graft for revision hip arthroplasty: biology and future applications, Clin. Orthop. Relat. Res. 417 (2003) 183–194, https://doi.org/10.1097/01.blo.0000096814.78689.77.

[3] V. Manavella, F. Romano, L. Corano, C. Bignardi, M. Aimetti, Three-dimensional volumetric changes in severely resorbed alveolar sockets after ridge augmentation with bovine-derived xenograft and resorbable barrier: a preliminary study on CBCT imaging, Int. J. Oral Maxillofac. Implant. 33 (2) (2018) 373–382, https://doi.org/10.11607/jomi.5684.

[4] T.N. Board, S. Brunskill, C. Doree, C. Hyde, P.R. Kay, R.D. Meek, R. Webster, G. Galea, Processed versus fresh frozen bone for impaction bone grafting in revision hip arthroplasty, Cochrane Database Syst. Rev. 4 (2009) CD006351, , https://doi.org/10.1002/14651858.CD006351.pub2.

[5] M. Hinsenkamp, L. Muylle, T. Eastlund, D. Fehily, L. Noel, D.M. Strong, Adverse reactions and events related to musculoskeletal allografts: reviewed by the World Health Organisation Project NOTIFY, Int. Orthop. 36 (3) (2012) 633–641, https://doi.org/10.1007/s00264-011-1391-7.

[6] D. Putzer, J. Fuchs, D. Coraca-Huber, A. Christoph, M. Liebensteiner, M. Nogler, BAG-S53P4 as an additive to bone allografts: a laboratory study using an uniaxial compression test, J. Orthop. Res. 33 (12) (2015) 1875–1879, https://doi.org/10.1002/jor.22953.

[7] H. Ohgushi, V.M. Goldberg, A.I. Caplan, Heterotopic osteogenesis in porous ceramics induced by marrow cells, J. Orthop. Res. 7 (4) (1989) 568–578, https://doi.org/10.1002/jor.1100070415.

[8] A.W. Blom, V. Wylde, C. Livesey, M.R. Whitehouse, S. Eastaugh-Waring, G.C. Bannister, I.D. Learmonth, Impaction bone grafting of the acetabulum at hip revision using a mix of bone chips and a biphasic porous ceramic bone graft substitute, Acta Orthop. 80 (2) (2009) 150–154, https://doi.org/10.3109/17453670902884767.

[9] S.S. Jensen, M.M. Bornstein, M. Dard, D.D. Bosshardt, D. Buser, Comparative study of biphasic calcium phosphates with different HA/TCP ratios in mandibular bone defects. A long-term histomorphometric study in minipigs, J. Biomed. Mater. Res. B Appl. Biomater. 90 (1) (2009) 171–181, https://doi.org/10.1002/jbm.b.31271.

[10] E. Clozza, M. Obrecht, M. Dard, P.G. Coelho, C. Dahlin, S.P. Engebretson, A novel three-dimensional analysis of standardized bone defects by means of confocal scanner and micro-computed tomography, Clin. Oral Investig. 18 (4) (2014) 1245–1250, https://doi.org/10.1007/s00784-013-1081-5.

[11] D.E. Hastings, S.M. Parker, Protrusio acetabuli in rheumatoid arthritis, Clin. Orthop. Relat. Res. 108 (1975) 76–83.

[12] D. Putzer, D. Coraca-Huber, A. Wurm, W. Schmoelz, M. Nogler, Optimizing the grain size distribution of allografts in bone impaction grafting, J. Orthop. Res. 32 (8) (2014) 1024–1029, https://doi.org/10.1002/jor.22635.

[13] H. Akiyama, T. Morishima, M. Takemoto, K. Yamamoto, H. Otsuka, T. Iwase, T. Kabata, T. Soeda, K. Kawanabe, K. Sato, T. Nakamura, A novel technique for impaction bone grafting in acetabular reconstruction of revision total hip arthroplasty using an ex vivo compaction device, J. Orthop. Sci. 16 (1) (2011) 26–37, https://doi.org/10.1007/s00776-010-0007-1.

[14] I.R. McNamara, Impaction bone grafting in revision hip surgery: past, present and future, Cell Tissue Bank. 11 (1) (2010) 57–73, https://doi.org/10.1007/s10561-009-9147-y.

[15] J.J. Arts, N. Verdonschot, P. Buma, B.W. Schreurs, Larger bone graft size and washing of bone grafts prior to impaction enhances the initial stability of cemented cups: experiments using a synthetic acetabular model, Acta Orthop. 77 (2) (2006) 227–233, https://doi.org/10.1080/17453670610045957.

[16] D. Putzer, C.G. Ammann, D. Coraca-Huber, R. Lechner, W. Schmolz, M. Nogler, The influence of liquids on the mechanical properties of allografts in bone impaction grafting, Biopreserv. Biobanking (2017), https://doi.org/10.1089/bio.2017.0003.

[17] A.C. Jones, C.H. Arns, A.P. Sheppard, D.W. Hutmacher, B.K. Milthorpe, M.A. Knackstedt, Assessment of bone ingrowth into porous biomaterials using MICRO-CT, Biomaterials 28 (15) (2007) 2491–2504, https://doi.org/10.1016/j.biomaterials.2007.01.046.

[18] D. Putzer, E. Mayr, C. Haid, A. Reinthaler, M. Nogler, Impaction bone grafting: a laboratory comparison of two methods, J. Bone Joint Surg. Br. 93 (8) (2011) 1049–1053, https://doi.org/10.1302/0301-620X.93B8.26819.

[19] M.A. Te Stroet, W.H. Rijnen, J.W. Gardeniers, A. van Kampen, B.W. Schreurs, Satisfying outcomes scores and survivorship achieved with impaction grafting for revision THA in young patients, Clin. Orthop. Relat. Res. 473 (12) (2015) 3867–3875, https://doi.org/10.1007/s11999-015-4293-y.

[20] B.S. Waddell, F. Boettner, A. Gonzalez Della Valle, Favorable early results of impaction bone grafting with reinforcement mesh for the treatment of paprosky 3B acetabular defects, J. Arthroplast. 32 (3) (2017) 919–923, https://doi.org/10.1016/j.arth.2016.09.037.

[21] T. Marshall, J. Chow, B. Sivakumar, N. Ahmed, P. Smith, Efficient use of a limited resource femoral head allograft: a comparison of allograft preparation methods, J. Orthop. Surg. 25 (3) (2017) 2309499017727952, , https://doi.org/10.1177/2309499017727952.

[22] R. Elfring, M. de la Fuente, K. Radermacher, Assessment of optical localizer accuracy for computer aided surgery systems, Comput. Aided Surg. 15 (1–3) (2010) 1–12, https://doi.org/10.3109/10929081003647239.

[23] M. Klemm, T. Kirchner, J. Grohl, D. Cheray, M. Nolden, A. Seitel, H. Hoppe, L. Maier-Hein, A.M. Franz, MITK-OpenIGTLink for combining open-source toolkits in real-time computer-assisted interventions, Int. J. Comput. Assist Radiol. Surg. 12 (3) (2017) 351–361, https://doi.org/10.1007/s11548-016-1488-y.

[24] M. Klemm, Intraoperative Planning and Execution of Arbitrary Orthopedic Interventions Using Handheld Robotics and Augmented Reality, Ph.D. thesis Karlsruher Institut für Technologie (KIT), 2018.

[25] D. Putzer, F. Scholl, L. Dankl, D. Dammerer, M. Thaler, M. Nogler, Intraoperative bone defect measurement in the acetabulum using a navigation system: the influence of bone porosity on the digitalization process, Med. Eng. Phys. 59 (2018) 75–80, https://doi.org/10.1016/j.medengphy.2018.06.005.

[26] L. Puri, B. Lapinski, R.L. Wixson, J. Lynch, R. Hendrix, S.D. Stulberg, Computed tomographic follow-up evaluation of operative intervention for periacetabular lysis, J. Arthroplast. 21 (6 Suppl 2) (2006) 78–82, https://doi.org/10.1016/j.arth.2006.05.024.

[27] M. Aimetti, V. Manavella, L. Corano, E. Ercoli, C. Bignardi, F. Romano, Three-dimensional analysis of bone remodeling following ridge augmentation of compromised extraction sockets in periodontitis patients: a randomized controlled study, Clin. Oral Implant. Res. 29 (2) (2018) 202–214.

[28] V. Manavella, F. Romano, F. Garrone, M. Terzini, C. Bignardi, M. Aimetti, A novel image processing technique for 3D volumetric analysis of severely resorbed alveolar sockets with CBCT, Minerva Stomatol. 66 (3) (2017) 81–90, https://doi.org/10.23736/S0026-4970.17.04029-8.

[29] C. Albert, B. Masri, C. Duncan, T. Oxland, G. Fernlund, Impaction allografting–the effect of impaction force and alternative compaction methods on the mechanical characteristics of the graft, J. Biomed. Mater. Res. B Appl. Biomater. 87 (2) (2008) 395–405, https://doi.org/10.1002/jbm.b.31117.

[30] L. Fosse, S. Muller, H. Rønningen, F. Irgens, P. Benum, Viscoelastic modelling of impacted morsellised bone accurately describes unloading behaviour: an experimental study of stiffness moduli and recoil properties, J. Biomech. 39 (12) (2006) 2295–2302 https://doi.org/10.1016/j.jbiomech.2005.07.014.

[31] D.C. Coraca-Huber, A. Wurm, M. Fille, J. Hausdorfer, M. Nogler, S. Vogt, K.D. Kuhn, Antibiotic-loaded calcium carbonate/calcium sulfate granules as co-adjuvant for bone grafting, J. Mater. Sci. Mater. Med. 26 (1) (2015) 5344, https://doi.org/10.1007/s10856-014-5344-8.