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Cross-Calibration of cortical bone parameters through CT-scans of embedded human vertebral bodies

Master-Project

At University of Applied Science Kiel
Department of Computer Science and Electrical Engineering

Degree Program: Master in Information Engineering

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1. Introduction:

CT-Scan images are used in clinical field to assess the patient health. In quantitative CT (QCT) parameters like volume, density, thickness, morphometric etc. of the bones can be estimated. Estimation of QCT parameters involve image processing steps like segmentation, registration and parametric analysis. Different CT-scanners and protocols affect image quality parameters like image resolution, noise, contrast, sharpness, slice thickness, grey level, image size and voxel size differently. Estimation of QCT parameters may change between CT-scanners, even for the same specimen. CT-scanners have different parameter settings from another like resolution, noise, contrast, pixel size, kernel, spatial frequency, number of projections, voltage, current, exposure etc. which can produce different results for same specimen. The aim of this project was to evaluate and quantify the differences in QCT for Cortical bone parameters when using different CT-scanners for manual segmentation compared to image registration methods. Methods of image processing are used to compare QCT parameters like cortical density and thickness between CT-scanners. Manual segmentation is time consuming but image processing methods are faster. This experiment was conducted to evaluate that which method performs better in terms of result, time and quality. Therefore, it can be used in future.

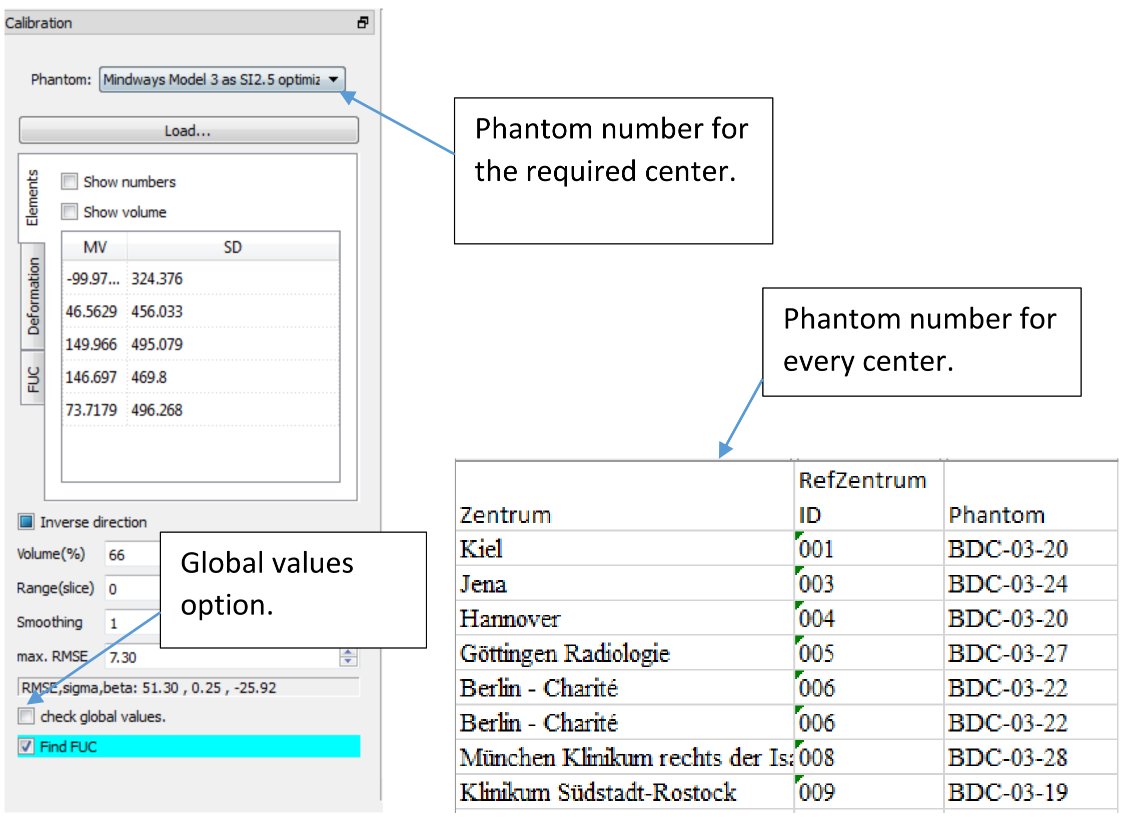
2. Material & Methods:

This section will present how the data was prepared for this project and explain every method which we applied to our data in detail.

2.1 Data and Image Pre-Processing:

For this project, six human vertebrae embedded in plastic material were scanned in eight different CT-scanners. Therefore, for each human vertebra we had eight different scans. In total we had 48 different vertebra scans available. The images were calibrated to density units with in-house developed software StructuralInsight. To perform calibration, following steps were undertaken:

1. In StructuralInsight dicom files of the vertebra scan were opened.
2. In Structural Insight selection of the appropriate phantom number for the center from calibration box is needed with checked box global values option. See Figure 1



Zentrum	RefZentrum ID	Phantom
Kiel	001	BDC-03-20
Jena	003	BDC-03-24
Hannover	004	BDC-03-20
Göttingen Radiologie	005	BDC-03-27
Berlin - Charité	006	BDC-03-22
Berlin - Charité	006	BDC-03-22
München Klinikum rechts der Is	008	BDC-03-28
Klinikum Südstadt-Rostock	009	BDC-03-19

Figure 1: Options to generate segmentation

3. After selecting the options fix the phantom template. See Figure 2

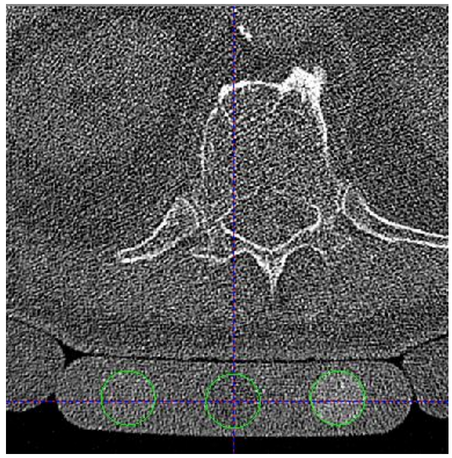


Figure 2: Adjust Volume

4. After that StructuralInsight automatically opened the dicom file with a smaller field of view (FOV) and smaller pixel spacing of the same vertebra. Region box  mode from the above tool bar helped to extract the vertebra from all views. See Figure 3

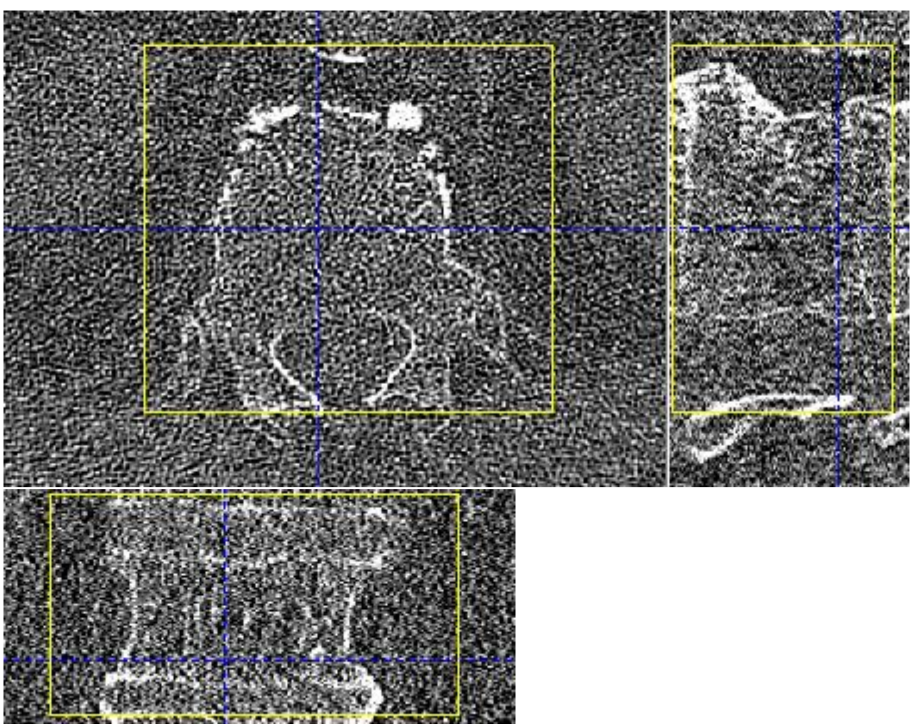


Figure 3: Extraction of Vertebra

5. Crop button from the above tool bar helped to crop the selected vertebra.
6. Finally, after all these our calibrated image was ready.

After calibration, next step was to perform segmentation to generate the mesh files for all vertebrae. Segmentations were created by using a shape-model algorithm developed by Mr. Stefan Reinhold (Multimedia Information Processing Group, CAU Kiel). To do so following steps were followed:

1. Extension of the slice file was changed from .xml to .bst. Batch file was used to change the extension of all files at once. Check StructuralInsight manual for rename command.
2. Mesh file was generated from the model file defaultConfig.yml. Different parameter settings (scaling, rotation, sigmaE, sigmaS, xyz and iterations) were tested to generate good meshes. Those are the most sensitive parameters to generate a good mesh for the vertebra images. For this project, we used the following parameter settings to get accurate segmentations:
   Origin:
   - Type: relative
   - Xyz: [0.5, 0.5, 0.5]
   - Scale: [1.4, 1, 1]
   - Rotation: [0, 180, 0]
   - sigmaE: 3
   - sigmaS: 2

   The effect of the parameters on segmentations are different like:
   - xyz: xyz values move the mesh to the respective axis.
   - Scale: Scale values increase or decrease the segmentation size to the respective axis. An increase in the x value will increase the size of segmentation to x axis.
   - Rotation: It will rotate the segmentation by the respective angle.
   - SigmaE: This value affects the endplate segmentation. Lower value shrinks the segmentation, higher value expands it.
   - SigmaS: This value affects the vertical cortex or the cut pedicles.
3. A batch file “**run_serial_CortidQCT_CLI**” was created to run the shape model algorithm. There, the .bst file (vertebra scan volume) was specified as input and .SIMesh file as output.
4. The batch file was executed to generate the meshes. Results could be viewed in StructuralInsight.

Alignment or rotation of the vertebra was needed to align the images because the images was not correctly aligned to the center of rotation [1]. Therefore, it will align the images to the center.

A batch file with the rotation command was created to align all images at once. After performing all above steps the data was ready for next steps.

2.2 Image Segmentation:

Image processing is a rapidly growing technique. It is a vast collection of technologies and procedures to extract information from images. In our daily lives, we encounter many technologies which are using image processing algorithm. As we know that CT-scans can be depict as an images and our motivation is to compare vertebra-scans which were scanned on eight different CT-scanners. Therefore, two methods were evaluated to perform our analysis.

2.2.1 Manual Segmentation:

Our first method was to segment all the files manually. Automatic generated segmentations which we generated while preparing our data were unfortunately not so perfect. Therefore, manual segmentation still took 4 to 5 hours per image to get it ready for the image processing.

2.2.1.1 Manual Mesh Adjustment:

To adjust the segmentations of the vertebrae following steps were followed:

1. Auto generated mesh was not good enough so the parameters in the model was changed in model file defaultConfig.yml and run that model again on that vertebra until the .SIMesh file was good enough.
2. The mesh was corrected for each slice and changed by dragging the points. Each point is presenting a specific part of the vertebra. Parts of vertebra are vertical cortex, upper end plate, lower end plate, cut pedicles and foramen. The points were moved towards the boundary line for each vertebra slice. Mesh Points can be seen in Figure 4

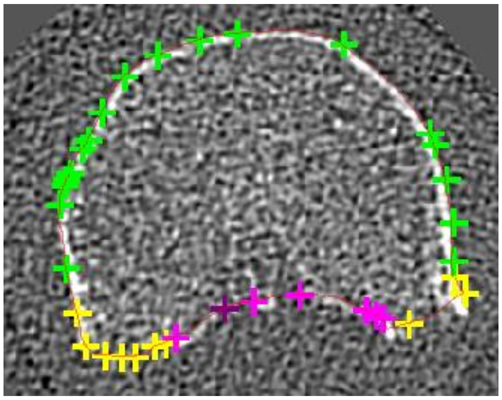


Figure 4: Vertebra Mesh

2.2.1.2 Relabeling:

1. After dragging the points towards boundary. Next step was to correct labels for the whole vertebra. To correct those labels, existed labels were removed from the mesh file. To remove the labels from mesh files Matlab script "Relabel_SIMesh_file.m" was executed. This script removed all the labels from the mesh file and saved the meshes without labels.
2. StructuralInsight was used to regenerate the labels. The labels were generated by drawing an angle on vertebra from the navigator tab. See Figure 5

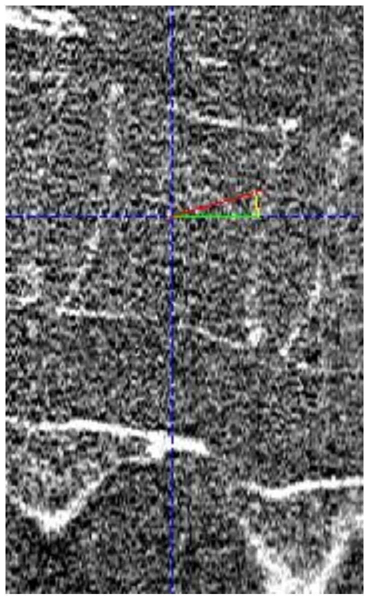


Figure 5: Segmentation generation using angle

3. The mesh was loaded on it and labels were generated automatically.
4. The labels were still not correct. Therefore, next step was to correct labels manually. To correct the labels manually important thing is to remember the color scheme and number for the labels of each part of vertebra such as:
    - Lower End Plate (color: Dark Blue, Number: 4)
    - Upper End Plate (color: Light Blue, Number: 5)
    - Foramen (color: Pink, Number: 6)
    - Cut Pedicle (color: Yellow, Number: 7)
    - Vertical Cortex (color: Green, Number: 3)

    For this analysis, the colors for lower and upper endplates were swapped. See below
    - Lower end plate (Original color: Light Blue, Segmentation color: Dark Blue)
    - Upper end plate (Original color: Dark Blue, Segmentation color: Light Blue)
5. The labels were changed by pressing the number of the respective part of the vertebra and clicked the + point on the mesh.

After manually re-segmenting and relabeling all the vertebrae. Segmentations were ready for image processing.

2.2.2 Image Registration:

The second method in the project was related to image registration technique. Image registration is the process of aligning two or more images of the same scenario. This process designate one image as the reference image and apply transformation to the other images [2]. For this method, there are two different registration approaches which were followed. For both approaches reference segmentations of one CT-scanner were used. These reference segmentations were collected from the first method where segmentations were done manually. Using these manual segmentations, data points could be mapped from one reference CT-scanner to other CT-scanner images.

2.2.2.1 Mask Registration:

First approach was to register masks from our reference set of images to the other scan images. In this approach only, segmented masks of reference images were mapped. It did not change the masks during mapping. To perform the mask registration following steps were followed:

1. Batch file was used to register the masks of reference CT-scan images to target CT-scan images. Check StructuralInsight manual for Registration mask command.
2. Run the batch file. It took about a half minute to run one file and storing the output. The resulting outputs were checked in StructuralInsight popup window.
3. The registration process not only create a registered output mask file. It generated a registration matrix file for each image file and checkboard images in StructuralInsight logs folder.
   Checkboard images are the overlap of both target and reference vertebra images. Those images show if both vertebrae are aligned properly. See Figure 6

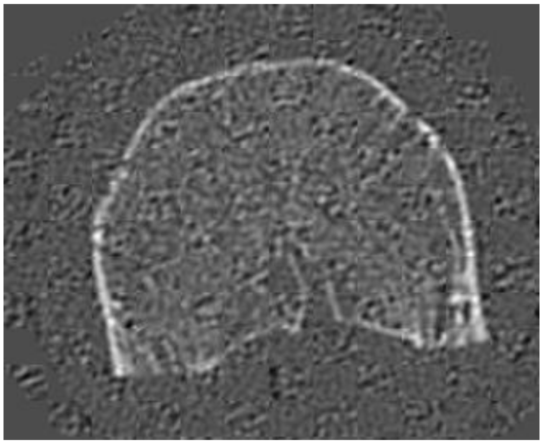
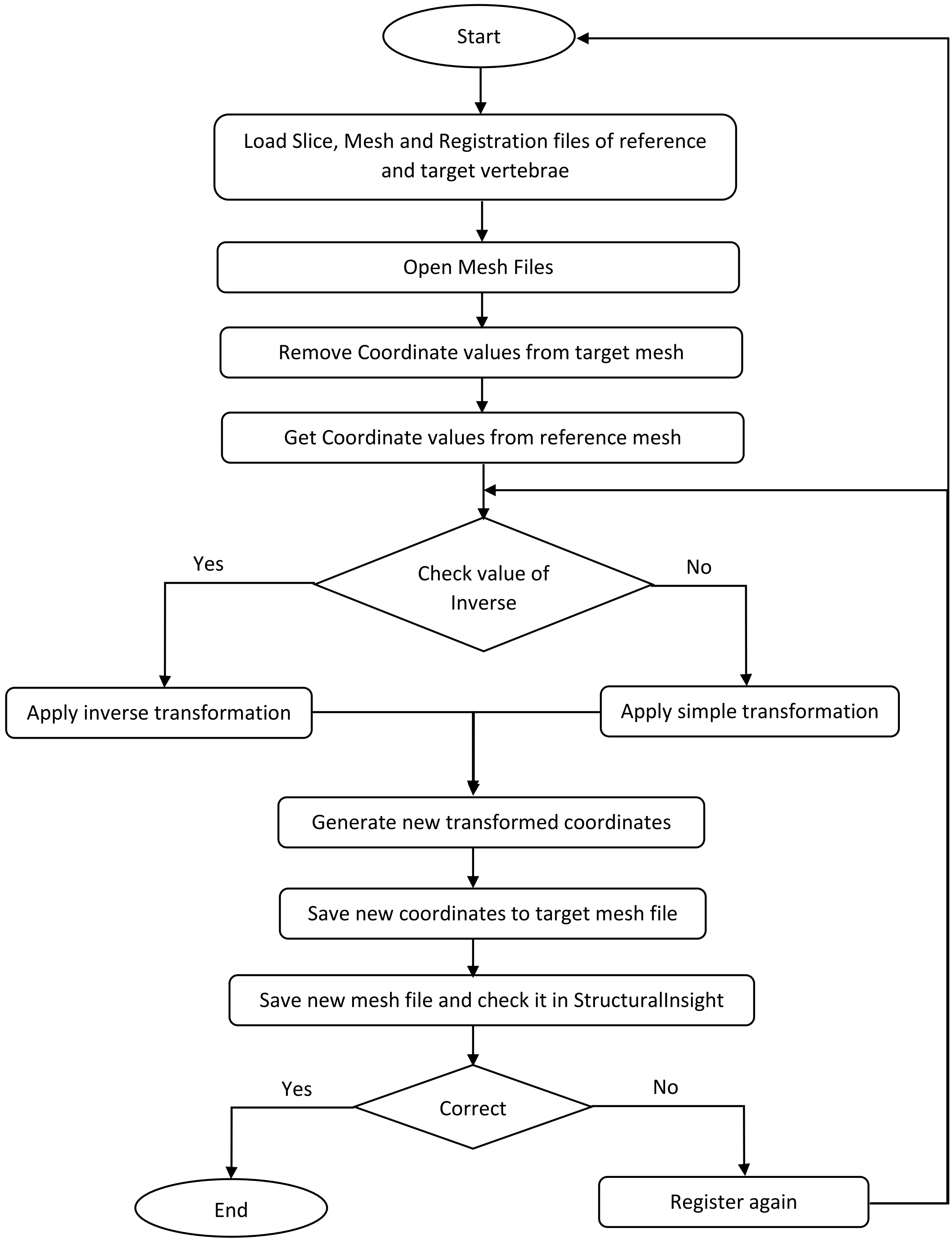


Figure 6: Check Board Image

2.2.2.2 Mesh Registration:

Second approach was to register mesh from our reference set images to other scan images. In this approach, the coordinate of each mesh was mapped from the reference to the target images. This method generated a new mesh and mask file for each image. It's similar to first method but automated. To perform the mesh registration following steps were followed:

1. All registration files were collected from StructuralInsight logs folder. Registration file consist of an inverse matrix, offset, rotation, angle, axis, translation and center points of both reference image and target image.
2. To automate the mesh registration process. A Matlab script "Mesh_Mapping.m" was written which mapped mesh coordinates from reference image to target image. The flow of the script is shown in Flowchart 1.
3. This script extract angles of each mesh point from both target and reference files. Then it gets values from the registration file. After getting values all angle values were multiplied with the calculated matrix value and update the angles in our target mesh file.
4. At the end script shows the output of one slice of our mapped target slice file. It shows if the mapping was successful or not.
5. The script was run for all files. All mapped meshes output were stored in output folder.
6. After that all files were verified on StructuralInsight.



Flowchart 1: Mesh Registration Process

3. Results:

To perform this experiment, three different methods were executed to check their performance. A Total of 48 vertebrae scans were processed for each method. The images of generated meshes, masks and regions for all three methods are shown below:

- **Manual Segmentation:**

  For all the files meshes were adjusted manually to make sure that each region is covered by the mesh and mask. The visual representation in Figure 7-8 shows how the mesh and regions look like in this method.

  Mesh:

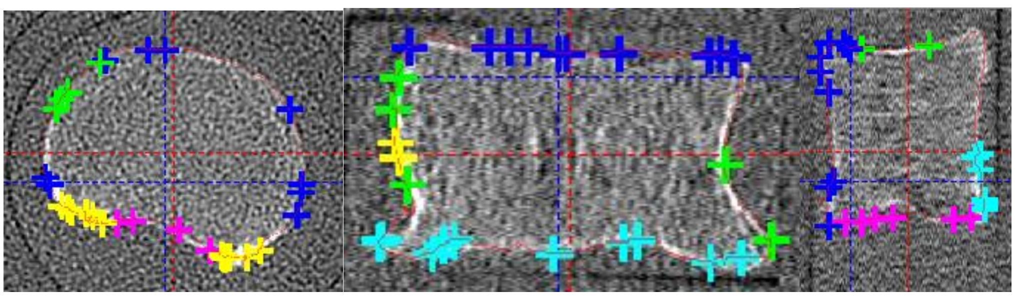


Figure 7: Visual View of Mesh

  Regions:

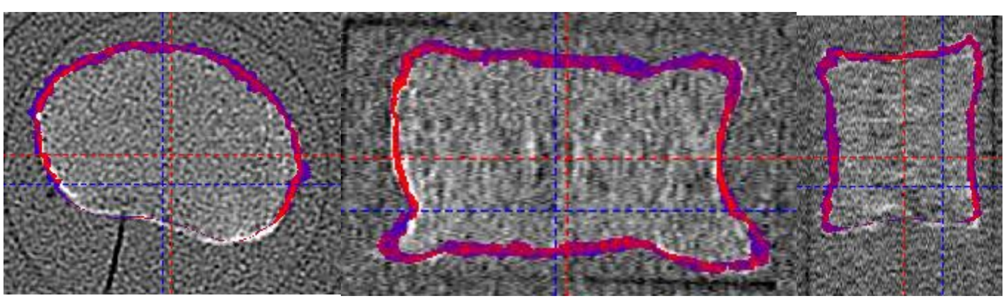


Figure 8: Visual View of Regions

- **Mask Registration:**

  Masks were generated by registering the mask of each vertebra from our reference group to target group. In this method no meshes were generated because only masks were mapped. The visual representation in Figure 9 shows how the regions look like in this method.

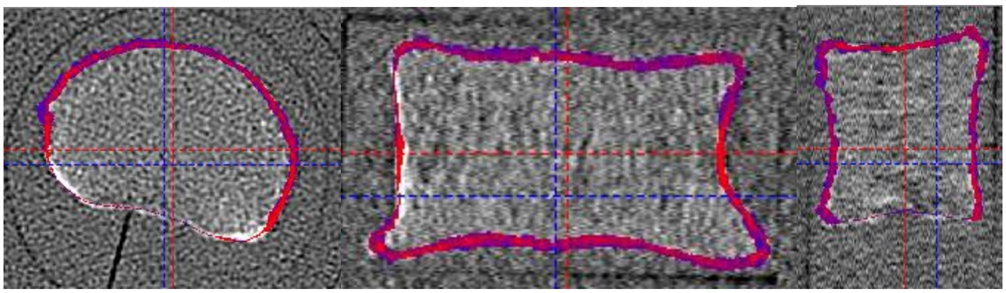


Figure 9: Visual View of Regions

- **Mesh Registration:**

  Meshes were generated by registering the mesh of each vertebra from our reference group to target group. This method is an automation of manual segmentation method. The visual representation in Figure 10-11 shows how the mesh and regions look like in this method.

  Mesh:

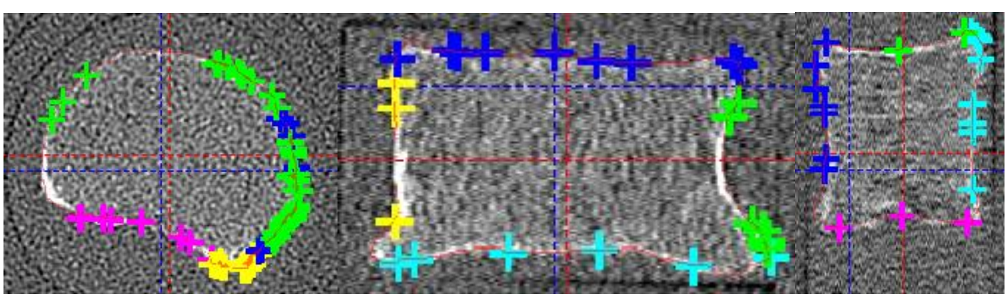


Figure 10: Visual View of Mesh

Regions:

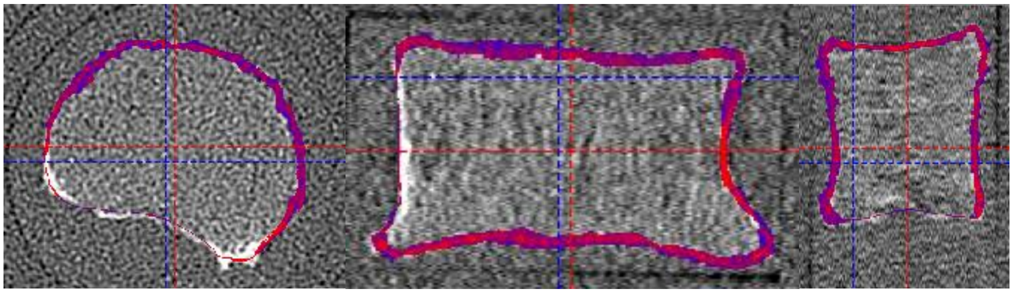


Figure 11: Visual View of Regions

Above detail representation of results in Figure 7-11 only show quantitative results. To make a better decision that which method has good results quantitative computed tomography (QCT) parameters plays an important role to check results on different regions of vertebra. For this project, four important regions of vertebra were selected:

- Cortex
- Vertical Cortex
- Lower Endplate
- Upper Endplate

There are a lot of QCT parameters which can be used to test the results on different regions but the most important parameters for this project was:

- Cortical Thickness (Ct.Th)
- Weighted Cortical thickness (wCt.Th)
- Cortical Thickness Standard Deviation (Ct.Th-SD)
- Total Volume (TV)
- Bone Mineral Density (BMD)

Given all regions and parameters the most important region for this project was Vertical Cortex and most important parameters were Weighted Cortical Thickness and Bone Mineral Density. Three different tests were performed on all three methods to check which one is better than others. The next sections will show the results of QCT parameters for all centers and methods only for Vertical Cortex region. Graphs for other regions are found in Appendix section.

3.1 Combined QCT Data Visualization:

For this analysis, we simply plot the values of each parameter with respect to all regions for all three methods and centers. Table 1 will show the average value of each parameter for all centers and methods. It also shows the mean and standard deviation for all parameters. The average values in between Manual and Mesh methods are very close to each other. The BMD values for all centers are very close in both methods, and same for weighted cortical thickness. The difference in average values can be seen in Figures 12-16 that which vertebrae or center is affecting the average values. Like for center 006_Berlin BMD value is bit higher in manual method than mesh because in Figure 16 value of vertebra v8 is higher than other center values which is affecting the value of average BMD value.

Figure 12-16 will show the analyzed values of each parameter for region Vertical Cortex. As you can see that the ranking of each vertebra in method manual and mesh is almost same or near to each other for all parameters. For mask method the values are same for all vertebrae because we just map the mask in this method and it's same to our reference center. For other regions the graphs are presented in Appendix A.

	ManualSeg					RegMask					RegMesh				
CenterID	Ct.Th	wCt.Th	Ct.Th-SD	TV	BMD	Ct.Th	wCt.Th	Ct.Th-SD	TV	BMD	Ct.Th	wCt.Th	Ct.Th-SD	TV	BMD
001_Kiel2018	1,347	0,512	0,412	2,530	477,093	1,347	0,512	0,412	2,530	477,093	1,347	0,512	0,412	2,530	477,093
003_Jena2013	1,306	0,464	0,372	2,475	442,078	1,307	0,436	0,397	2,429	413,651	1,377	0,480	0,417	2,493	433,220
003_Jena2018	1,340	0,478	0,410	2,428	445,736	1,323	0,473	0,413	2,531	444,833	1,343	0,481	0,418	2,427	445,499
004_Hannover2018	1,382	0,498	0,400	2,527	445,876	1,320	0,471	0,414	2,533	444,254	1,417	0,505	0,418	2,606	440,936
005_Goettingen2018	1,312	0,504	0,401	2,405	483,964	1,325	0,514	0,411	2,531	485,174	1,330	0,514	0,416	2,453	483,890
006_Berlin2015	1,217	0,494	0,373	2,114	510,111	1,339	0,499	0,409	2,530	466,064	1,283	0,496	0,405	2,263	489,417
008_Muenchen2016	1,411	0,459	0,354	2,668	397,088	1,321	0,424	0,408	2,531	398,919	1,451	0,469	0,380	2,677	396,195
009_Rostock2018	1,383	0,488	0,378	2,507	435,163	1,328	0,465	0,411	2,531	436,651	1,400	0,489	0,407	2,591	431,731
Overall Mean	1,337	0,487	0,388	2,457	454,639	1,326	0,474	0,409	2,518	445,830	1,368	0,493	0,409	2,505	449,748
Overall Standard Dev	0,061	0,019	0,021	0,160	34,737	0,012	0,033	0,005	0,036	29,901	0,054	0,016	0,013	0,128	31,732

Table 1: Average Parameter values for Vertical Cortex

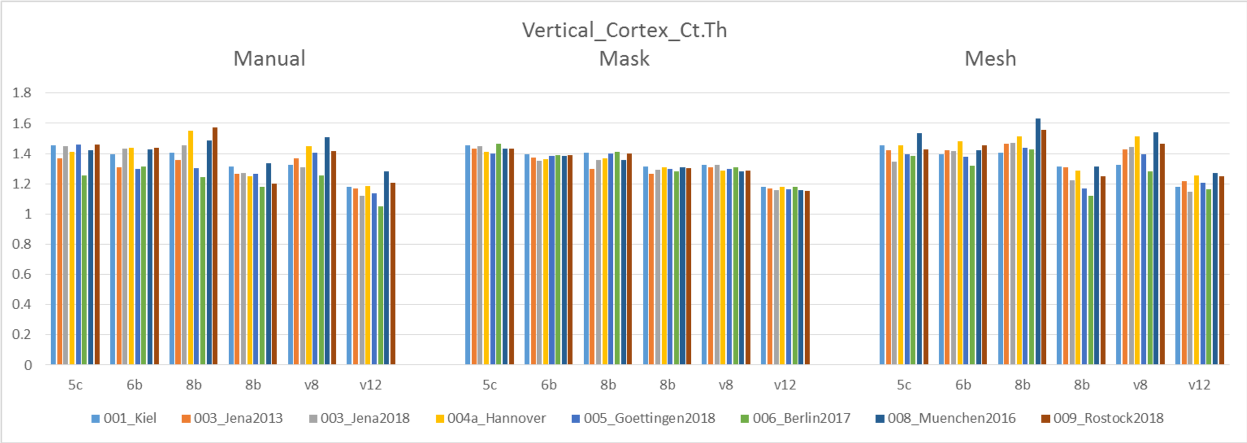


Figure 12: Values for Vertical Cortex Ct.Th

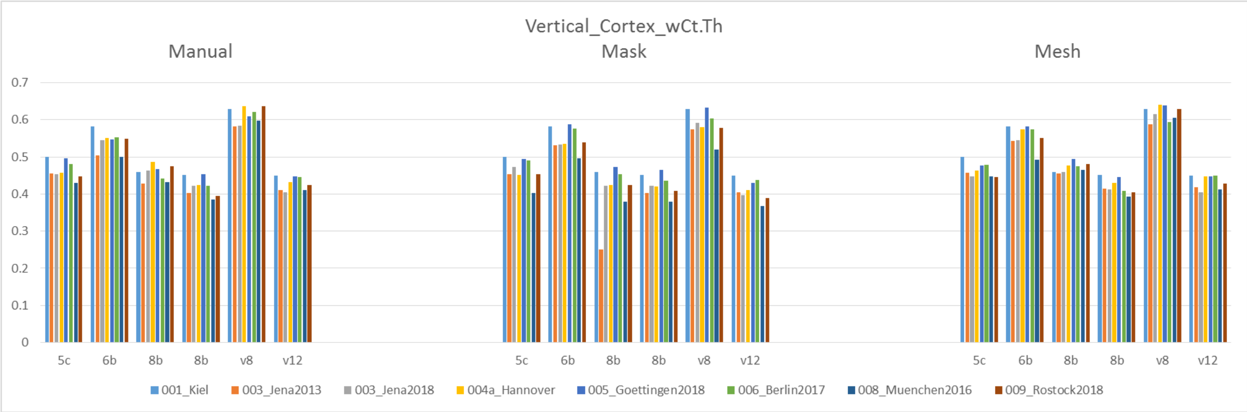


Figure 13: Values for Vertical Cortex wCt.Th

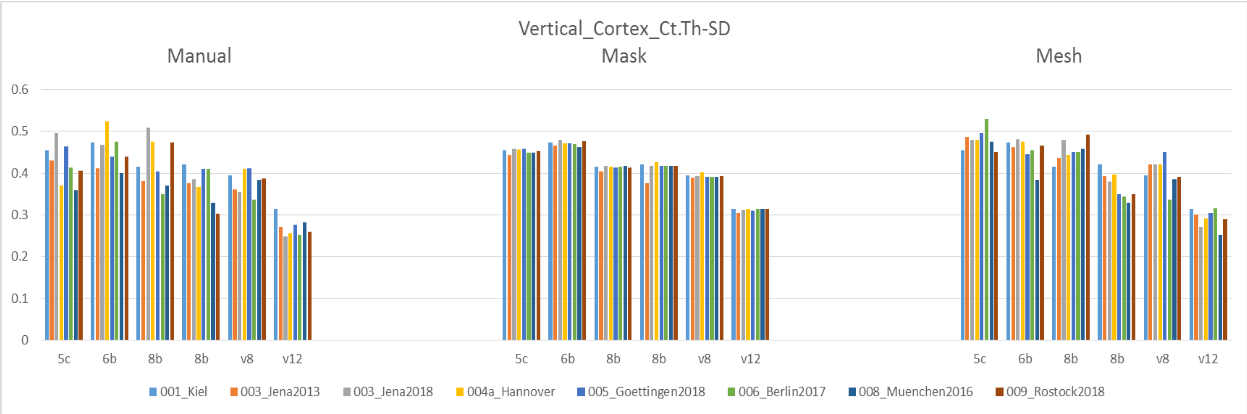


Figure 14: Values for Vertical Cortex Ct.Th-SD

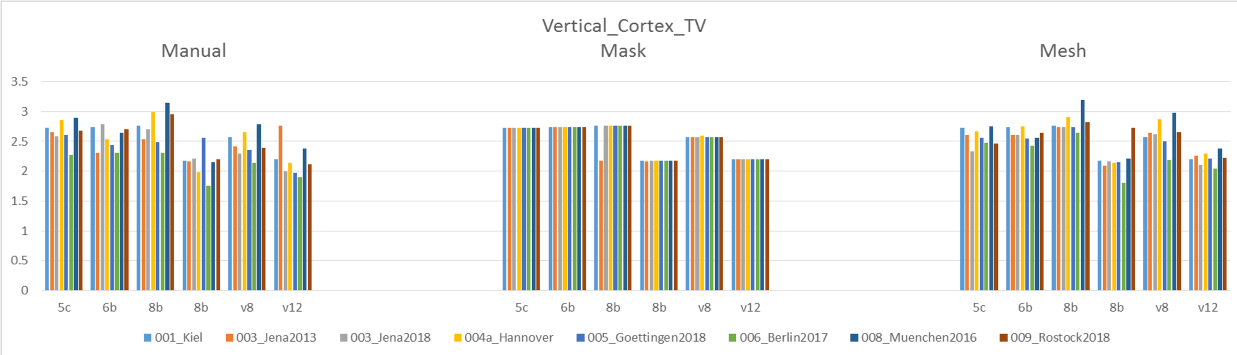


Figure 15: Values for Vertical Cortex TV

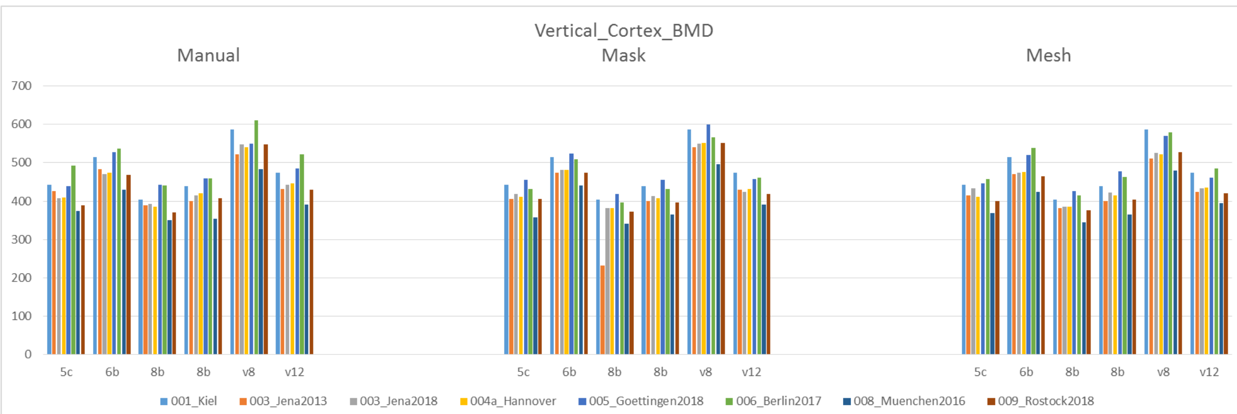


Figure 16: Values for Vertical Cortex BMD

3.2 Anova Test:

To check the credibility of the experiment Anova-test was conducted. The purpose of this test is to check if there are differences between the methods. Anova-Test helps us in deciding that the results of methods are significantly different or not from each other. To check the significance in between methods the p-value was checked for each parameter for every region. We set our p-value condition to 0.05. Which means if the p-value is lower than 0.05 than methods are significantly different otherwise they are similar. The p-values for all parameters and regions are listed in Table 2.

Box plots for Anova test will show the distribution of all vertebrae points for the selected region Vertical cortex. In Figures 17-21 it can be seen that the distribution in between manual and mesh methods are almost equal to each other. For mask method the points are very close to each other because we just map the mask for this method and nothing changed. For other regions the graphs are presented in Appendix B.

Region	**Veriable**	**P_value**
Cortex	Ct.Th	P < 661237.344
Cortex	wCt.Th	P > 0.003
Cortex	Ct.Th-SD	P > 0.015
Cortex	TV	P < 0.100
Cortex	BMD	P < 0.809
Lower_Endplate	Ct.Th	P < 29819774.312
Lower_Endplate	wCt.Th	P > 0.005
Lower_Endplate	Ct.Th-SD	P < 0.122
Lower_Endplate	TV	P > 0.001
Lower_Endplate	BMD	P < 0.794
Upper_Endplate	Ct.Th	P < 2483479006.492
Upper_Endplate	wCt.Th	P < 19706163259.492
Upper_Endplate	Ct.Th-SD	P < 0.160
Upper_Endplate	TV	P < 5226701002.239
Upper_Endplate	BMD	P < 0.259
Vertical_Cortex	Ct.Th	P < 0.153
Vertical_Cortex	wCt.Th	P < 0.460
Vertical_Cortex	Ct.Th-SD	P < 0.169
Vertical_Cortex	TV	P < 0.546
Vertical_Cortex	BMD	P < 0.792

Table 2: P-Values for all regions and parameters

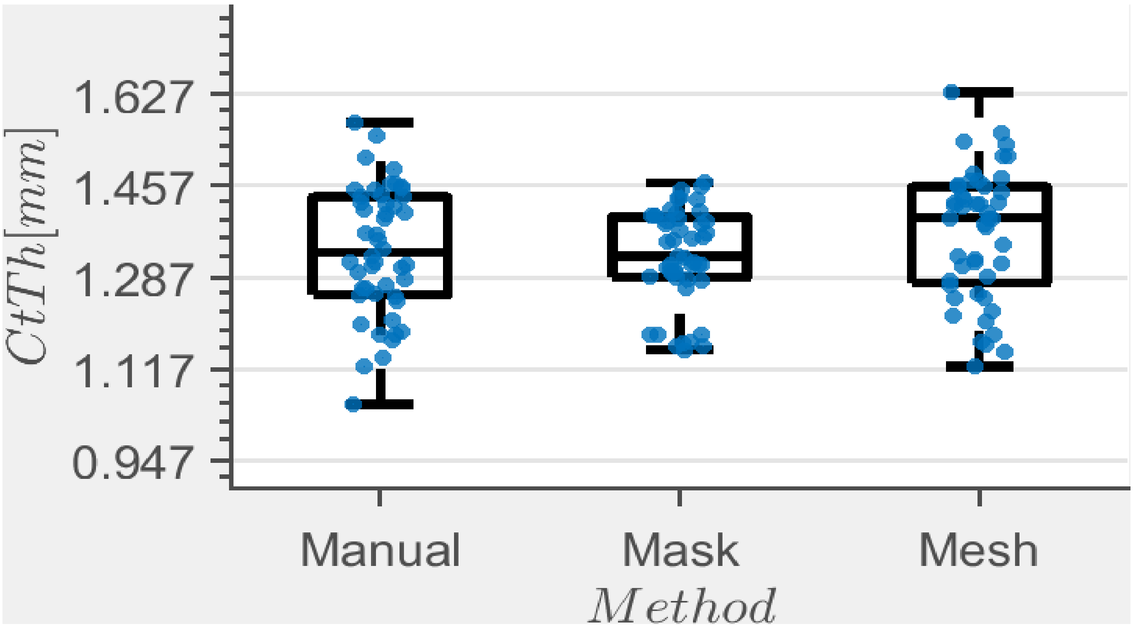


Figure 17: Anova graph for Vertical Cortex Ct.Th

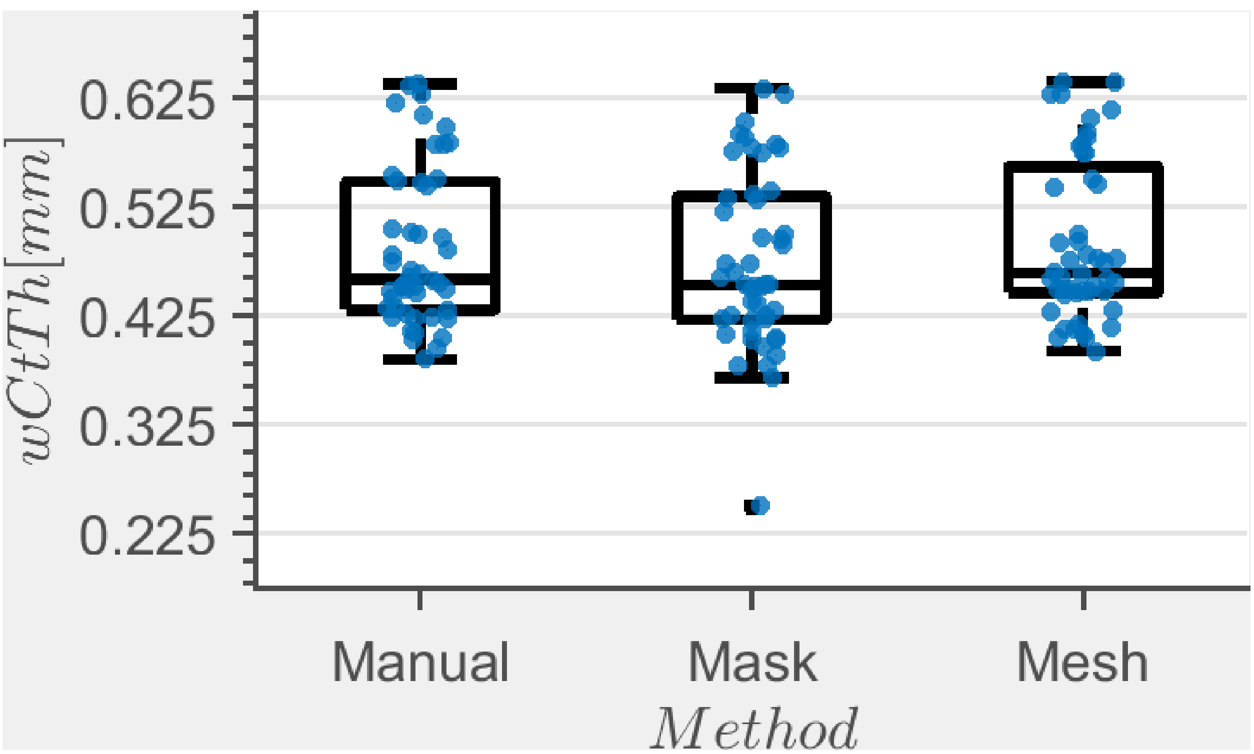


Figure 18: Anova graph for Vertical Cortex wCt.Th

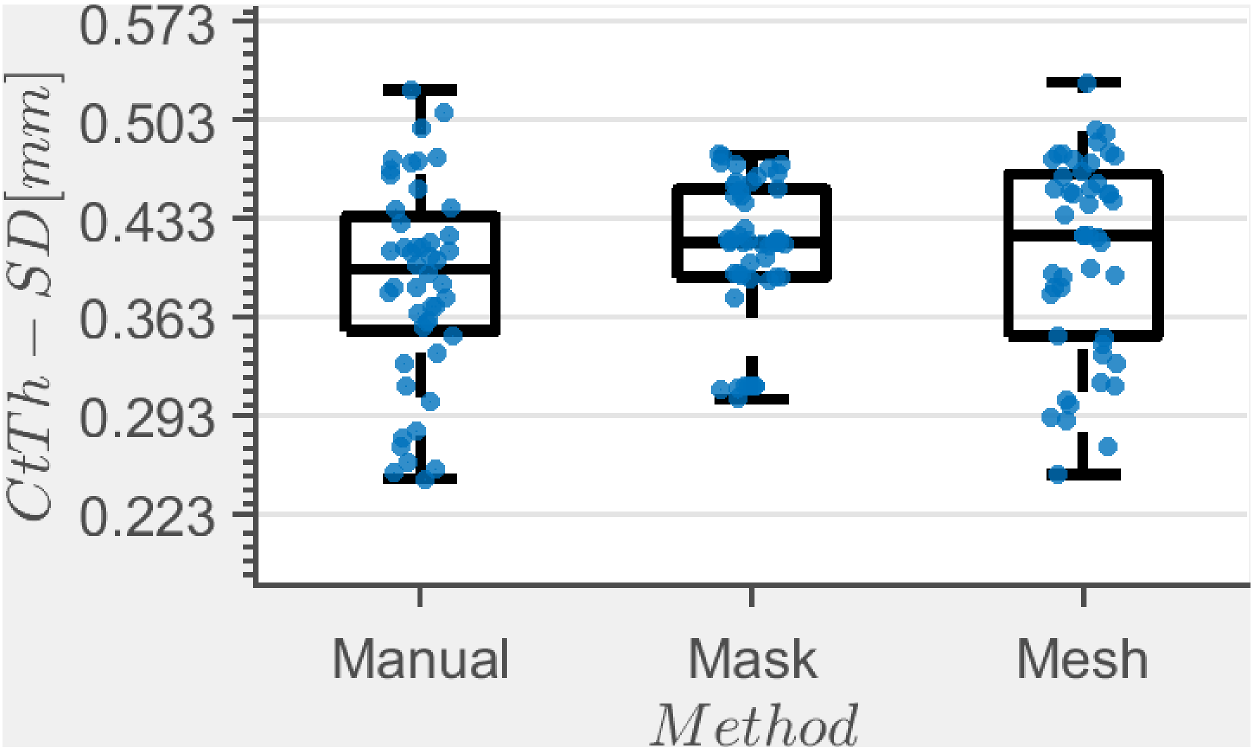


Figure 19: Anova graph for Vertical Cortex Ct.Th-SD

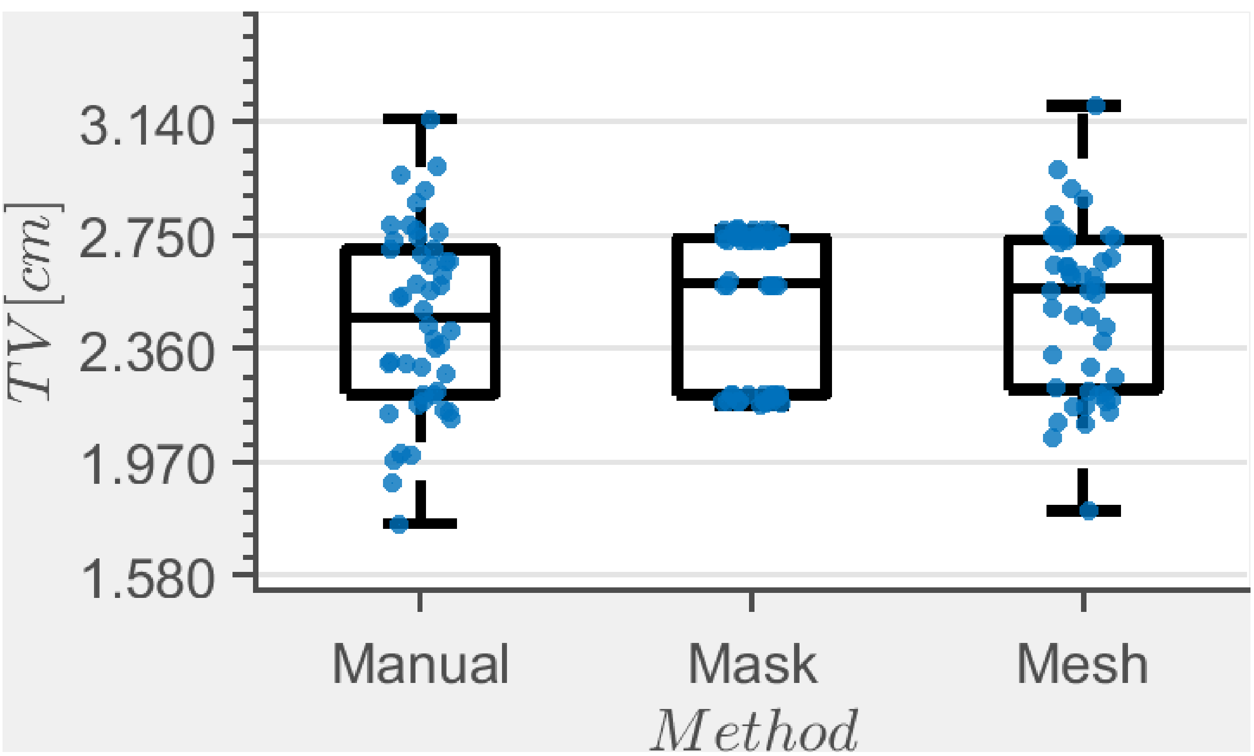


Figure 20: Anova graph for Vertical Cortex TV

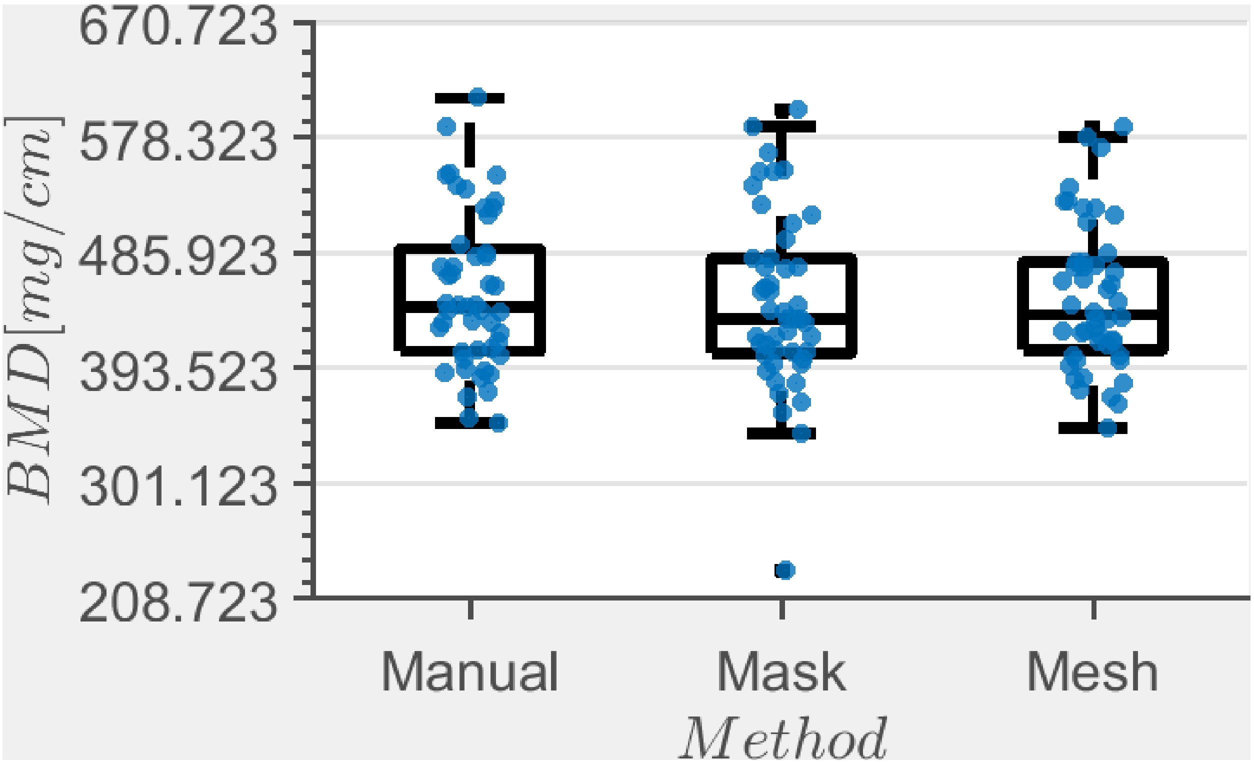


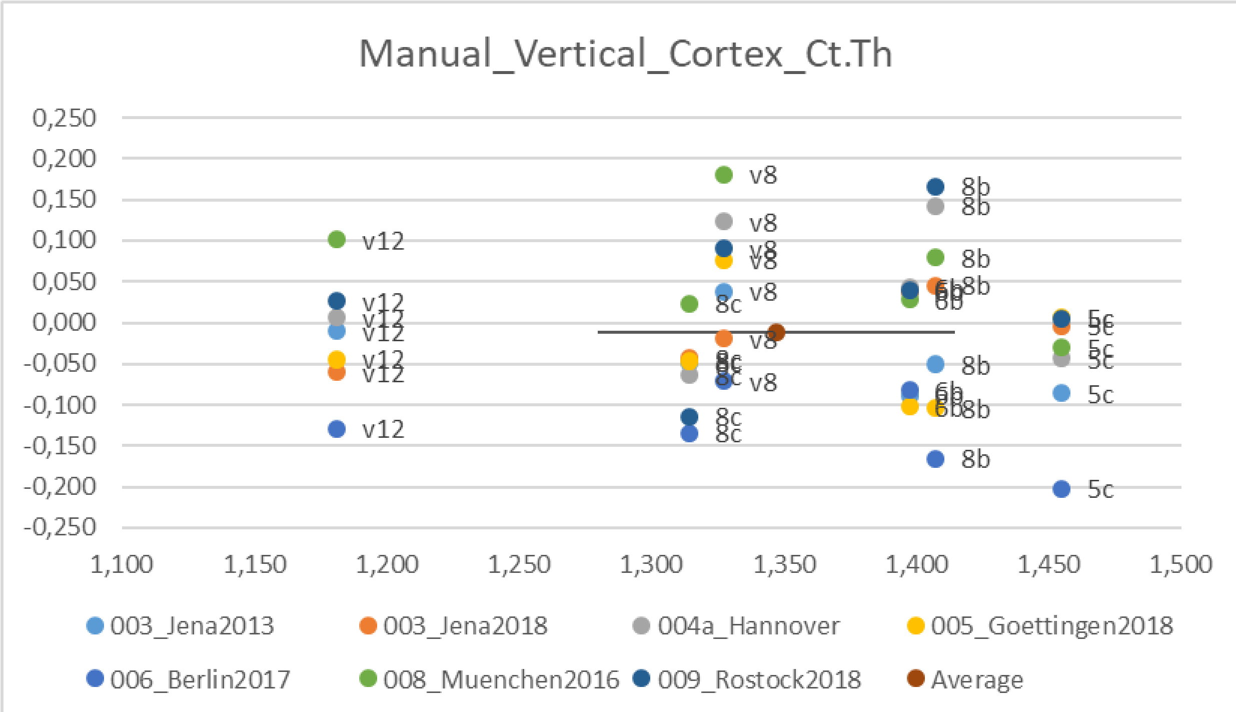
Figure 21: Anova graph for Vertical Cortex BMD

3.3 Bland-Altman Analysis:

In this analysis, mesh registration method was evaluated on the basis of the manual method. Mesh registration calculates the cortical parameters for a vertebra using the same coordinates across all centers. Therefore, to check the validity of these methods Bland-Altman was conducted. The purpose of this is to check any systematic difference between methods. It helps us in deciding which method is performing better. Table 3 will show the average difference for all parameters of vertical cortex region in between all methods. Average difference for all methods are closed to zero which means methods are not different from each other but for BMD average difference for all methods are higher. BMD has larger values which effect the average difference. Figures 22-26 will show the Bland-Altman results of method mesh registration and manual on selected region Vertical cortex too. For other regions the graphs and table are presented in Appendix C.

Difference Average/Method	Manual	Mask	Mesh
Ct.Th [mm]	-0.012	-0.024	0.024
wCt.Th [mm]	-0.028	-0.043	-0.021
Ct.Th-SD [mm]	-0.028	0.003	-0.003
TV [cm^3]	-0.084	0.014	-0.029
BMD [mg/cm^3]	-25.662	-35.409	-31.252

Table 3: Average Difference for all parameters in every method



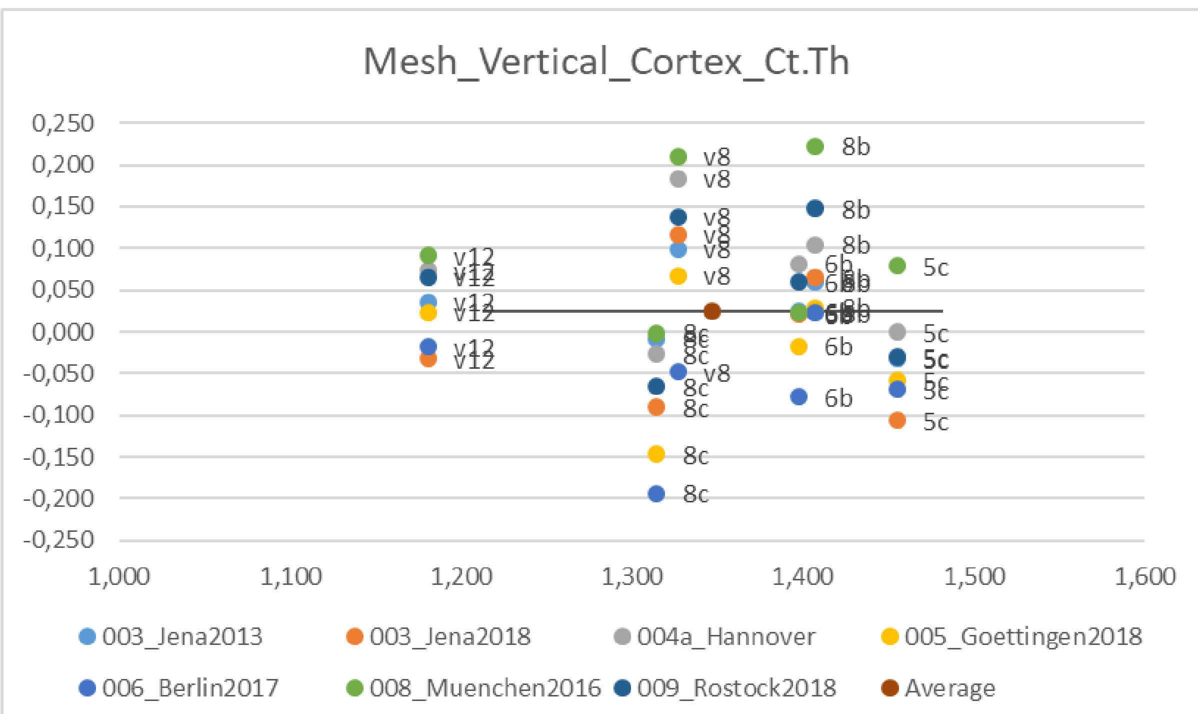
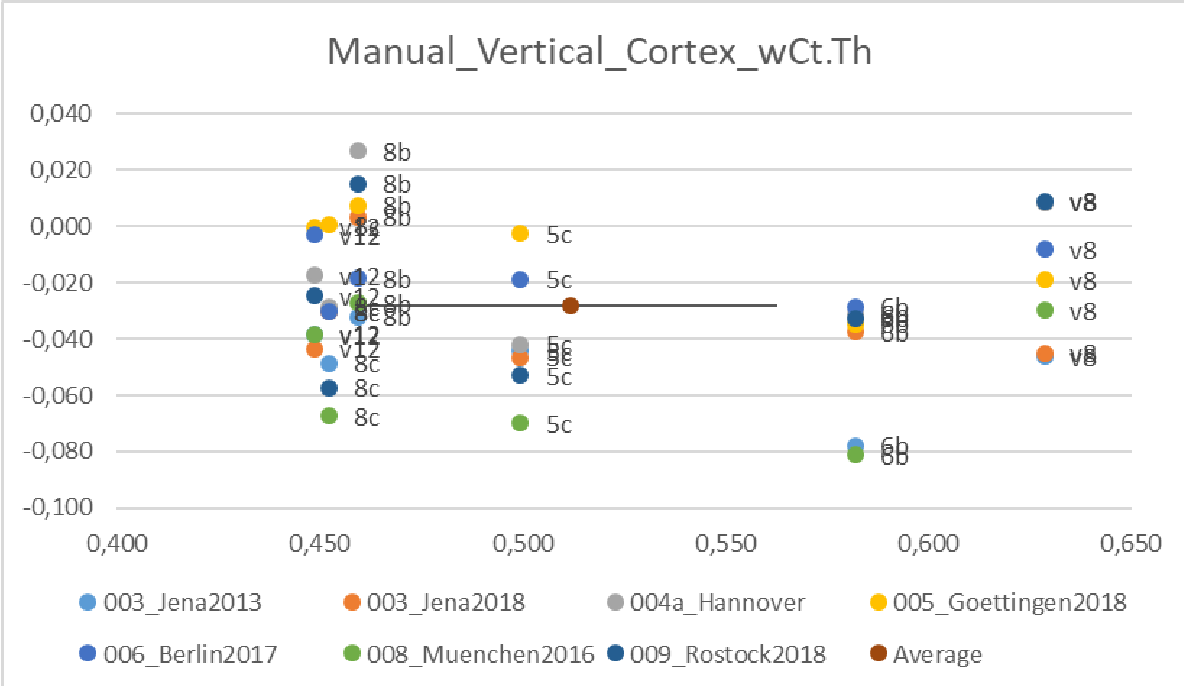


Figure 22: Compare Difference in between mesh and manual method for Ct.Th



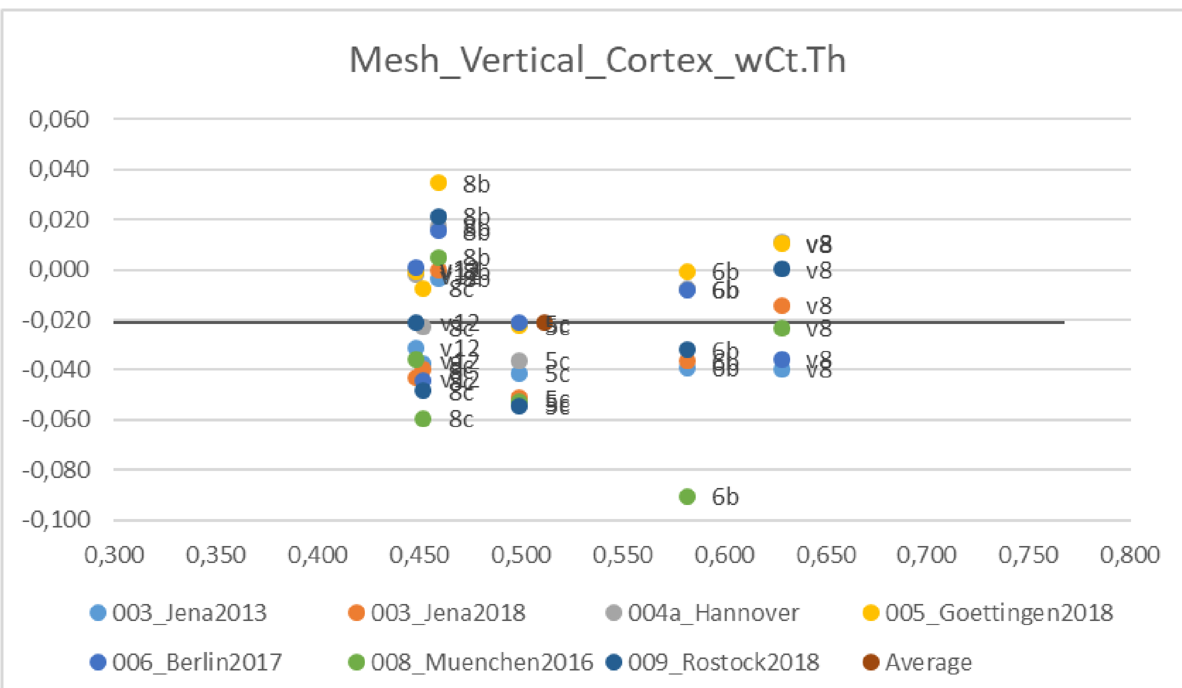
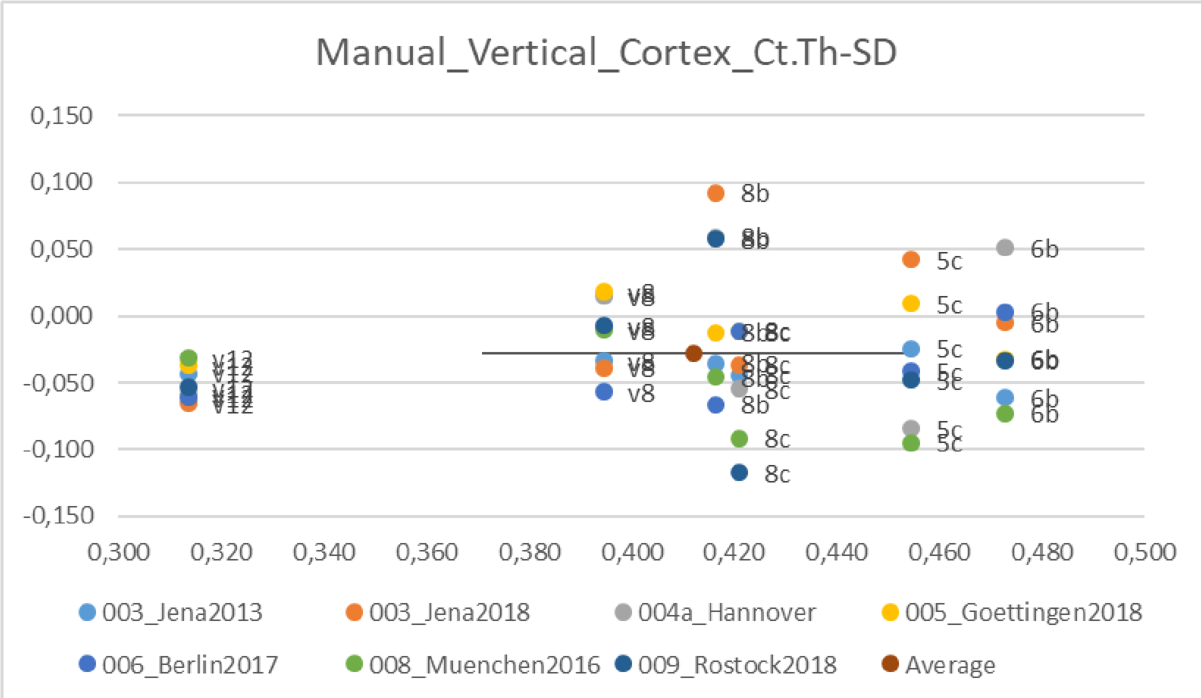


Figure 23: Compare Difference in between mesh and manual method for wCt.Th



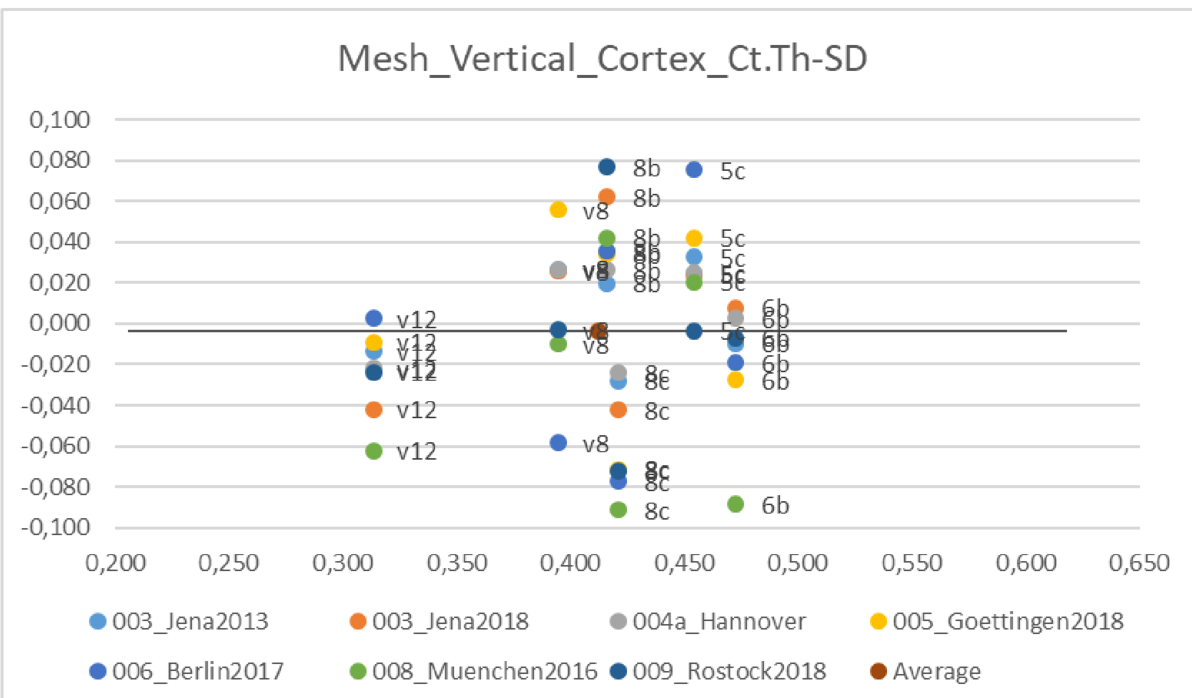
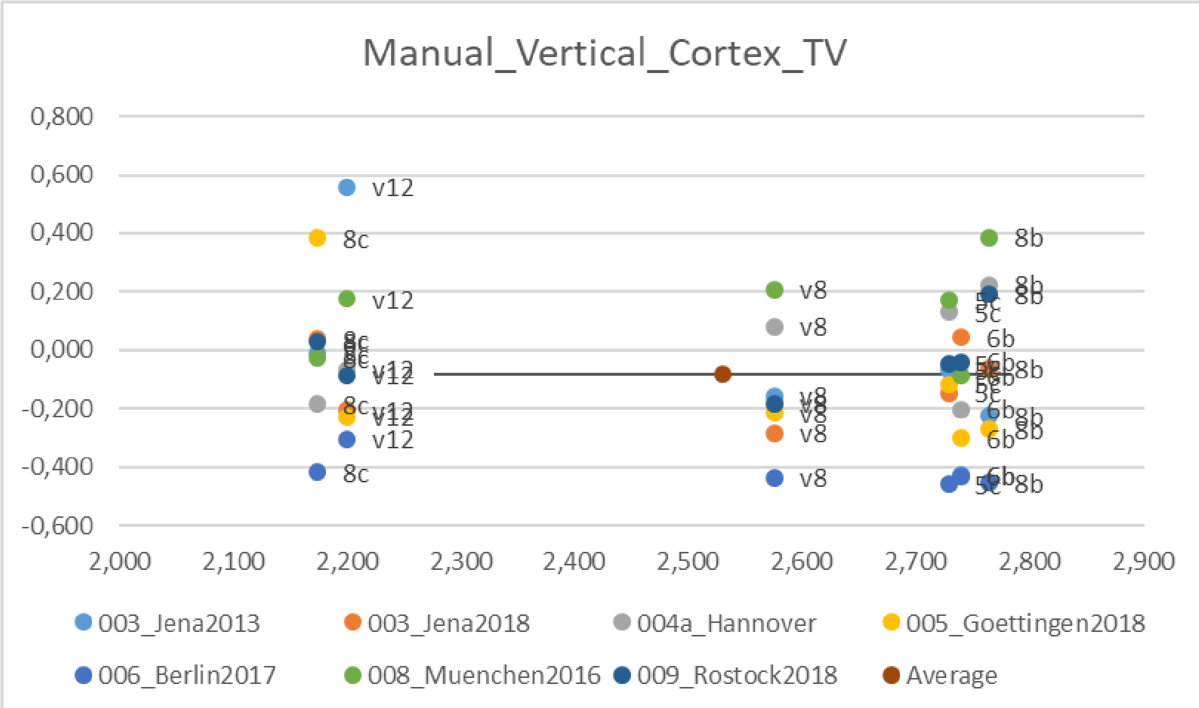


Figure 24: Compare Difference in between mesh and manual method for Ct.Th-SD



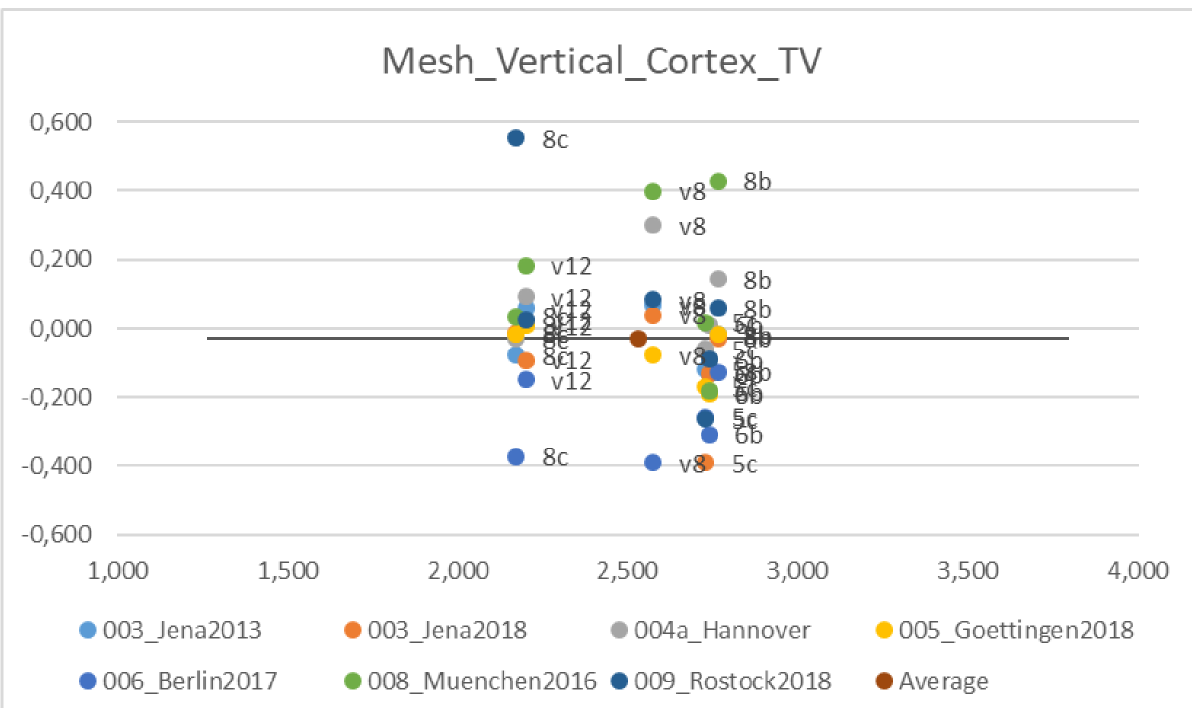
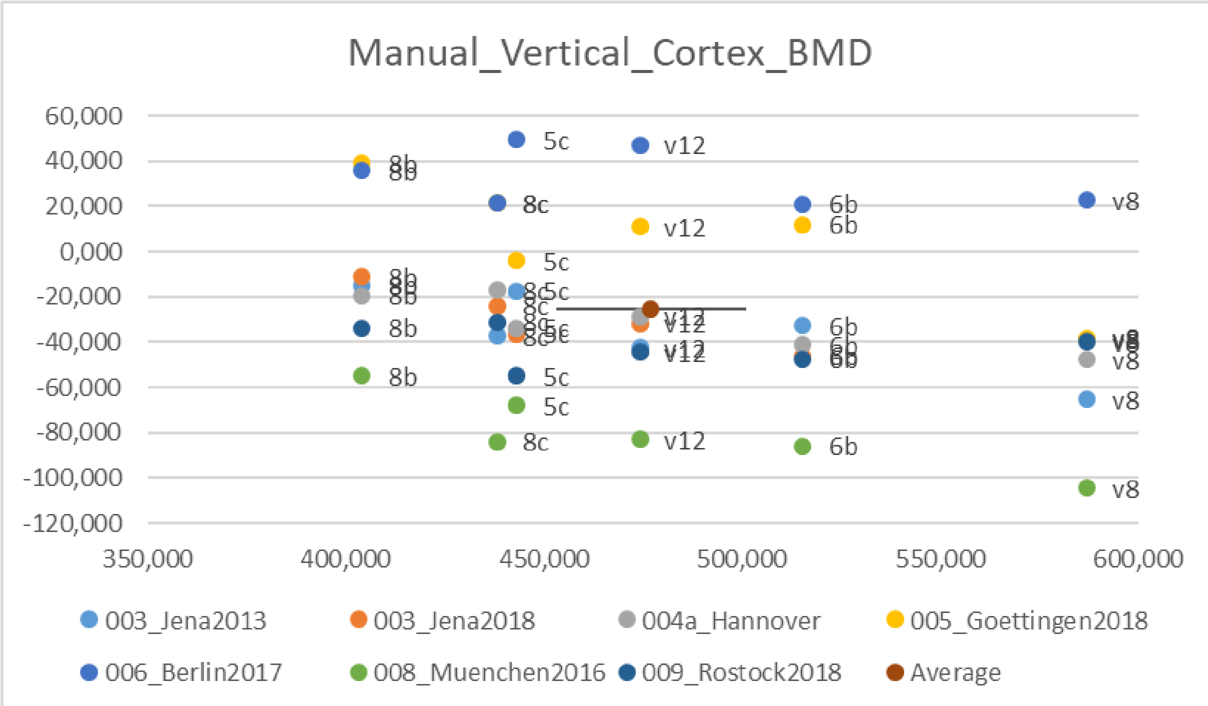


Figure 25: Compare Difference in between mesh and manual method for TV



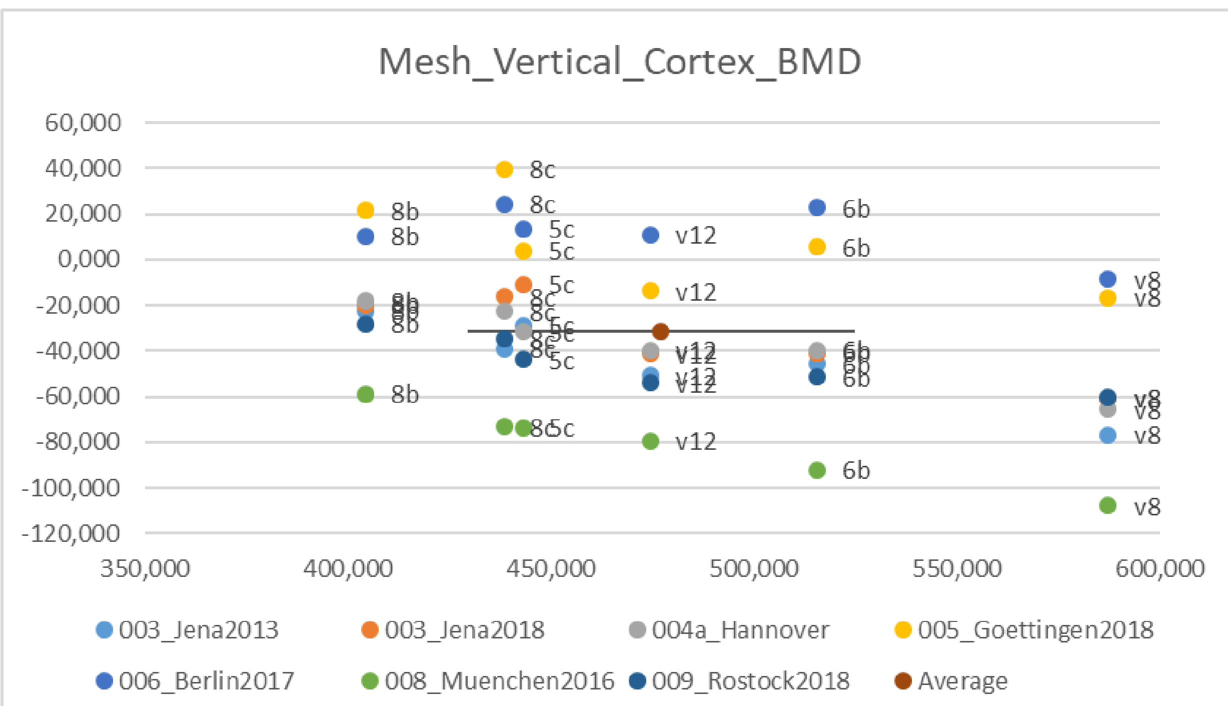


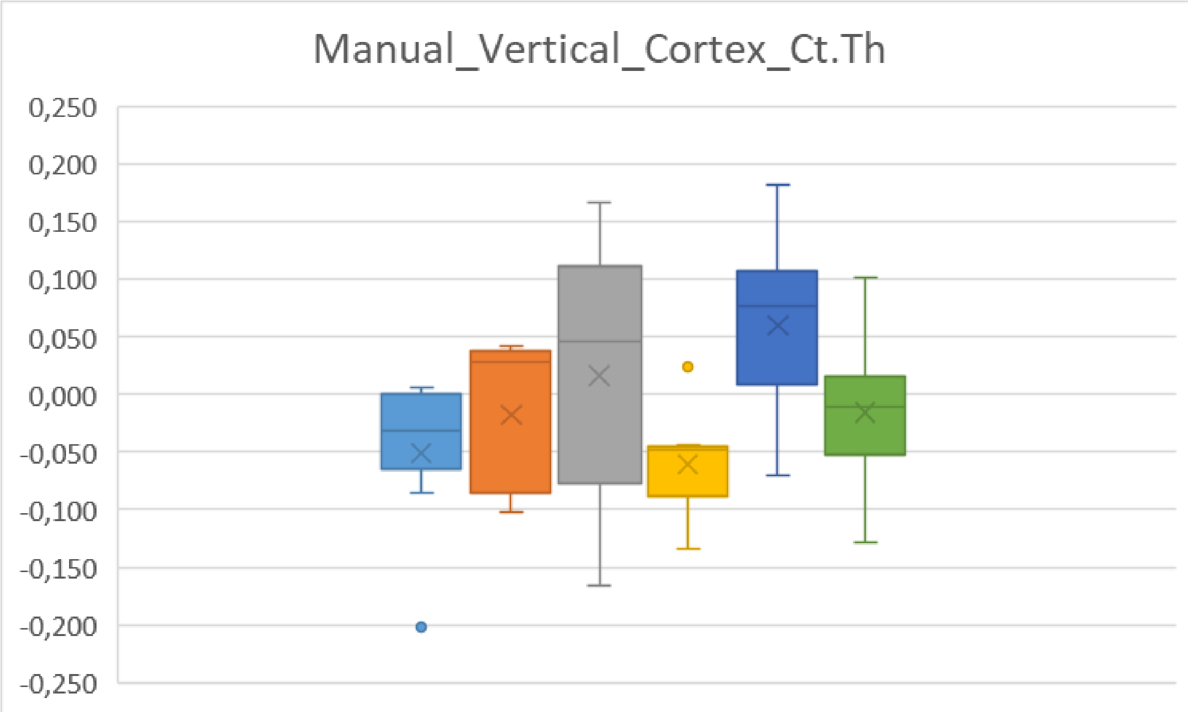
Figure 26: Compare Difference in between mesh and manual method for BMD

3.4 Box-Plot Analysis:

In our last analysis, again we evaluate mesh registration method on the basis of the manual method. Mesh registration is performing segmentation automatically. Therefore, it was our main interest to know if mesh and manual methods are close enough to each other. So, we can use mesh registration method in future and reduce the manual effort for creating segmentations. Therefore, to check the similarity of these methods Box plot analysis was conducted. The purpose of this is to check the distribution of data for both methods in between all centers and vertebrae. The distribution of data be easily seen in box plots because they contain all three quartiles, maximum and minimum values for the data. It helps us in deciding that mesh method is equally reliable or better than manual method. Table 4 discuss the difference and similarities in box plot graphs. Figures 27-31 will show the Box-Plot results of method mesh registration and manual on selected region Vertical cortex. For other regions the graphs are presented in Appendix D.

QCT Parameters	Results Summary
Ct.Th	Average difference in between reference center and other centers for method mesh and manual is similarly distributed for all vertebrae. Blue (5C) and green (V12) color vertebrae are same in both methods but others are different.
wCt.Th	Average difference in between reference center and other centers for method mesh and manual is similarly distributed for all vertebrae. Gray (8B) and yellow (8C) color vertebrae have higher values in manual method but other are same in both methods.
Ct.Th-SD	Average difference in between reference center and other centers for method mesh and manual is not similarly distributed for all vertebrae. All vertebrae have lower values in mesh method than manual.
TV	Average difference in between reference center and other centers for method mesh and manual is bit highly distributed for some vertebrae. All vertebrae have lower values in mesh method than manual.
BMD	Average difference in between reference center and other centers for method mesh and manual is similarly distributed for all vertebrae. Gray (8B), dark blue (V8) and green (V12) have higher values in manual method.

Table 4: Similarities and difference in Box-plot graphs



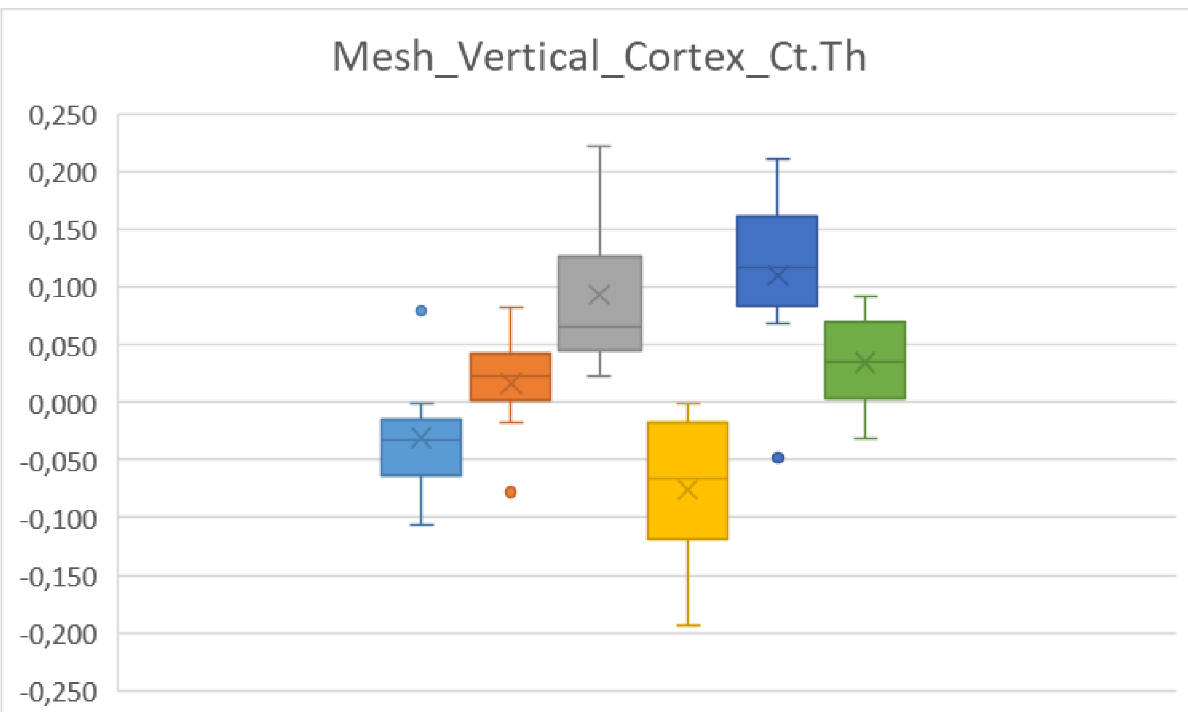
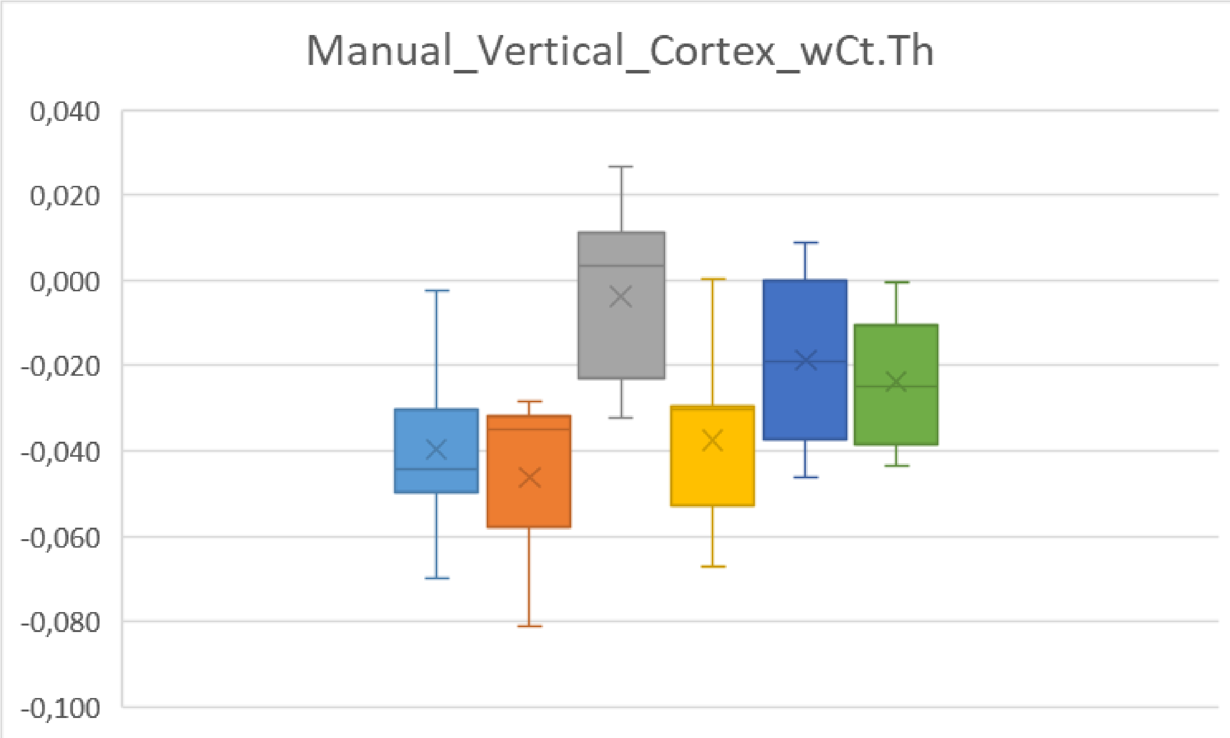


Figure 27: Compare Box-Plots of mesh and manual method for Ct.Th



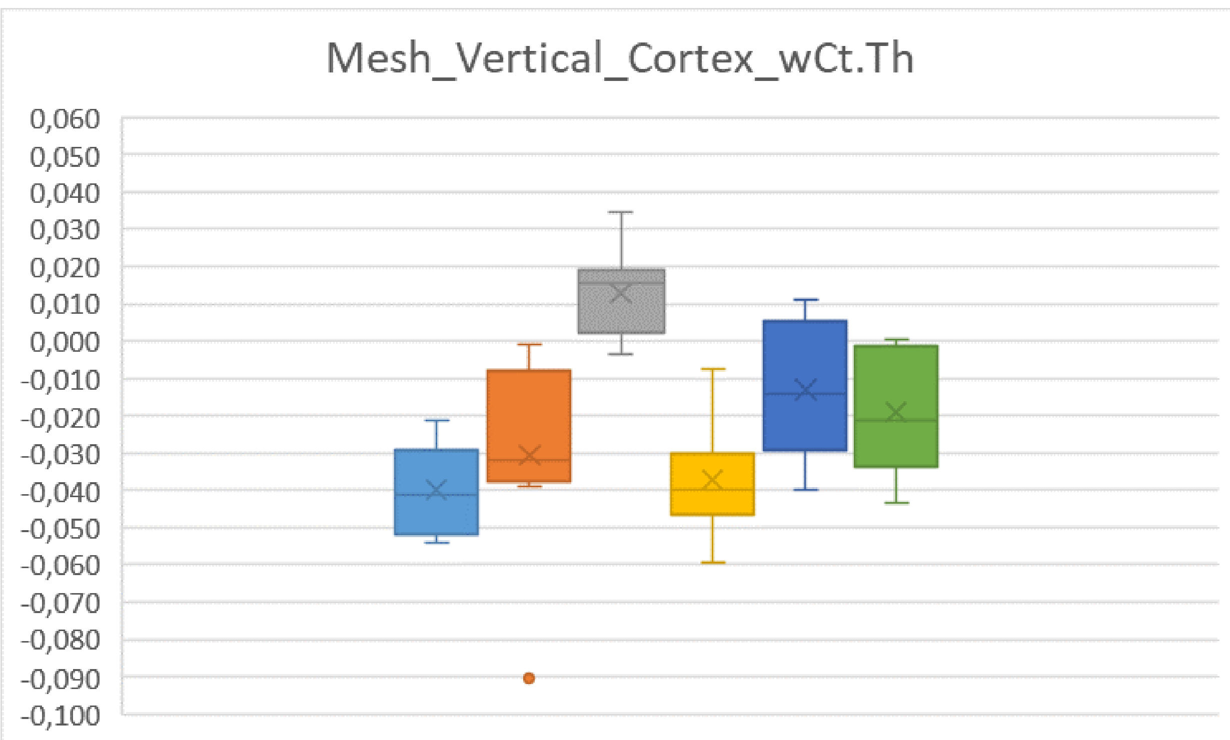
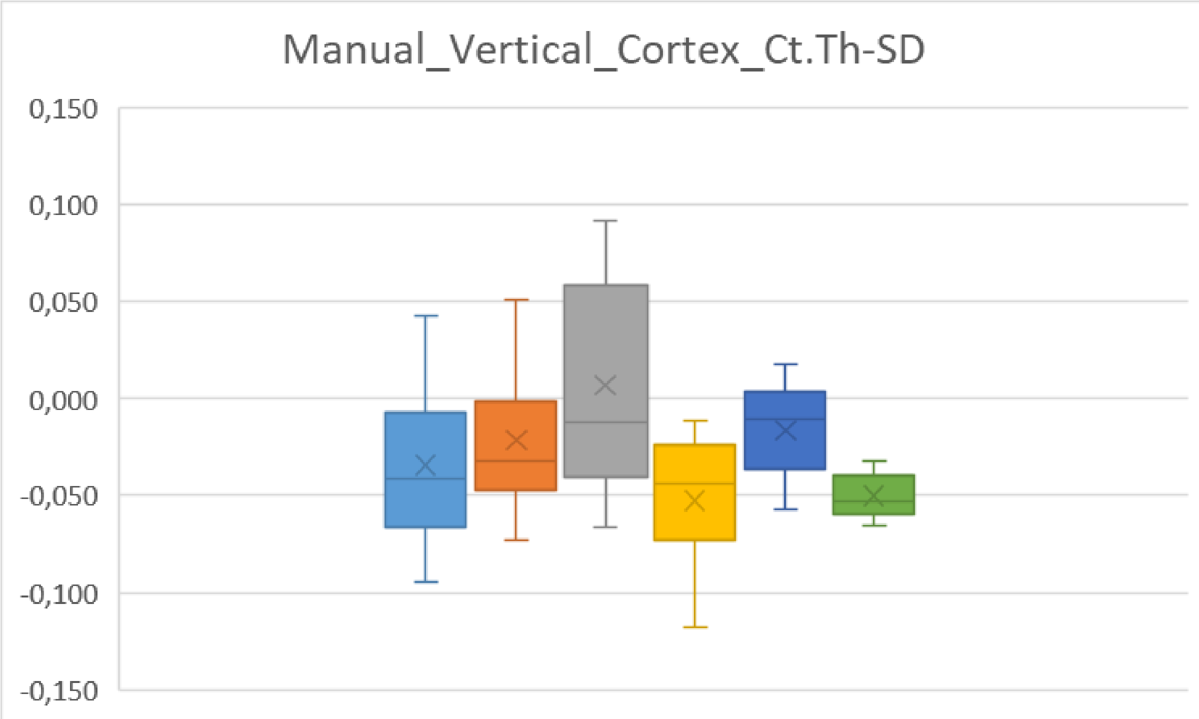


Figure 28: Compare Box-Plots of mesh and manual method for wCt.Th



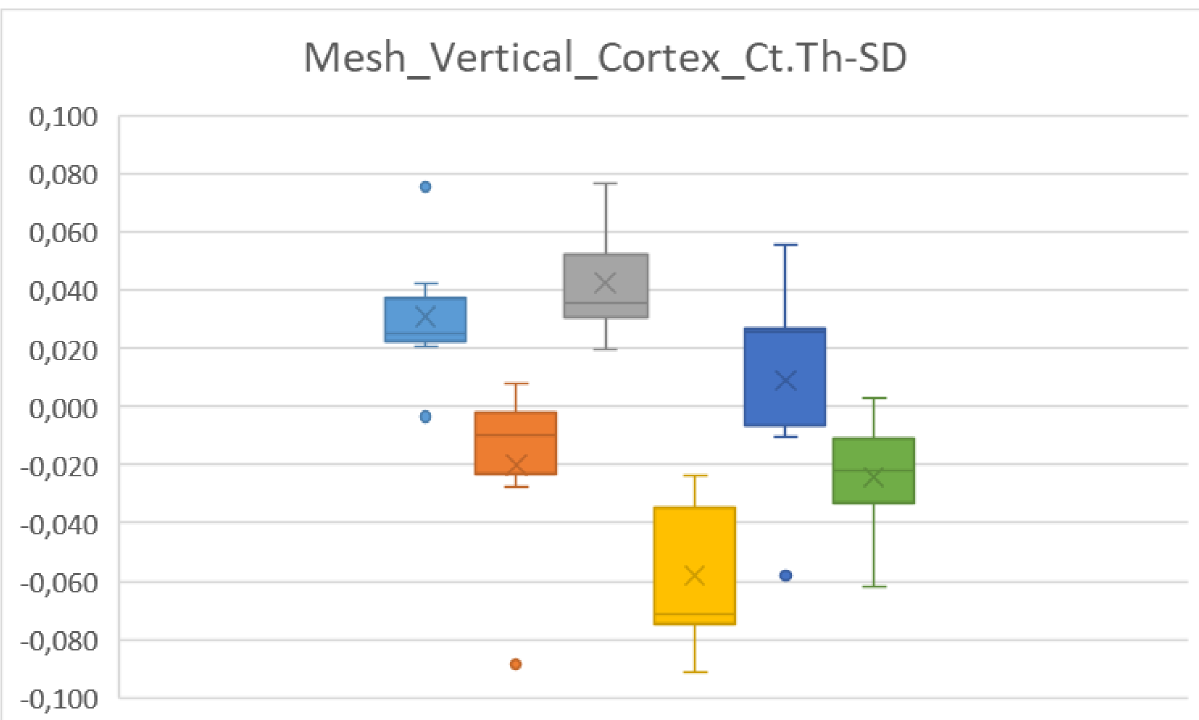


Figure 29: Compare Box-Plots of mesh and manual method for Ct.Th-SD

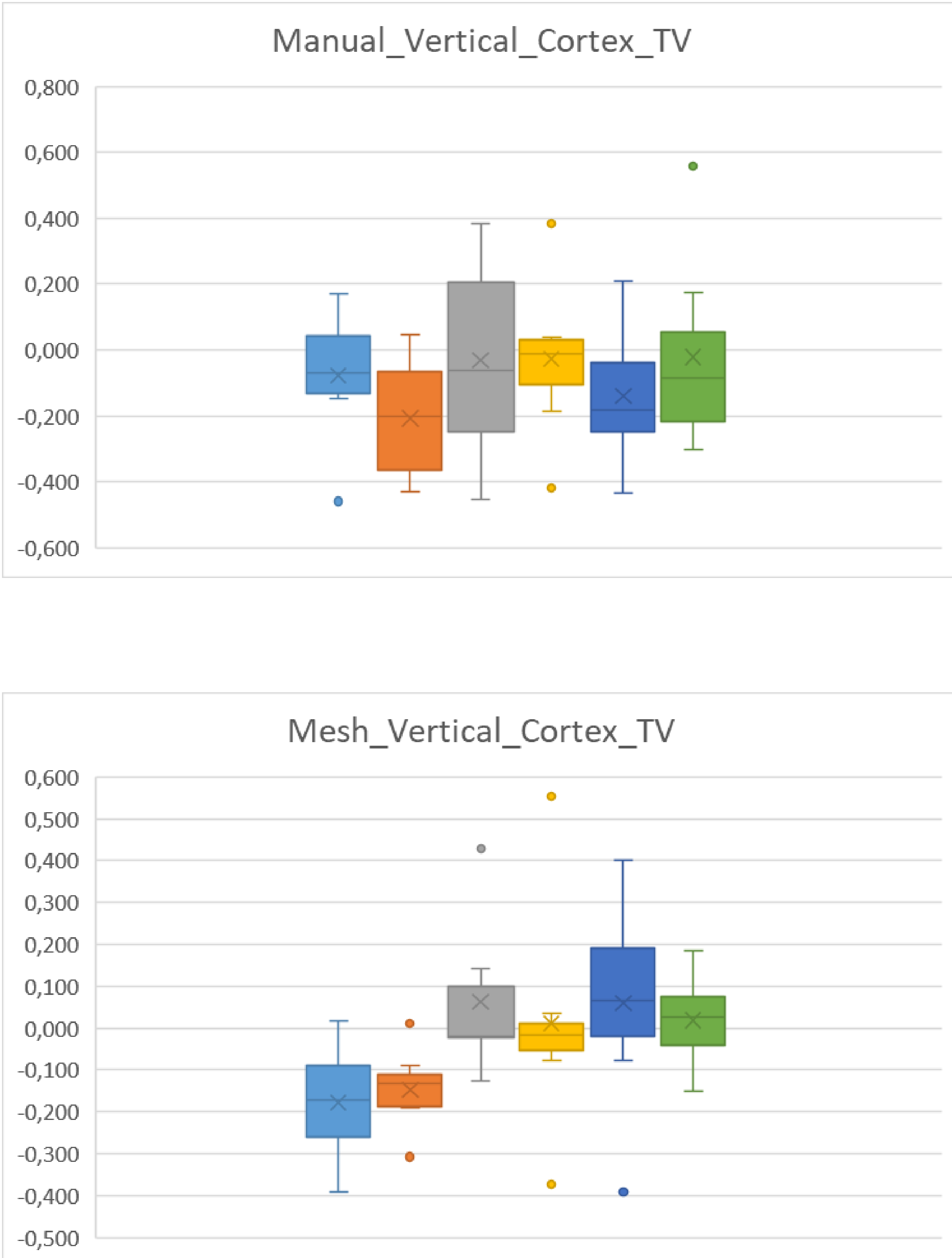
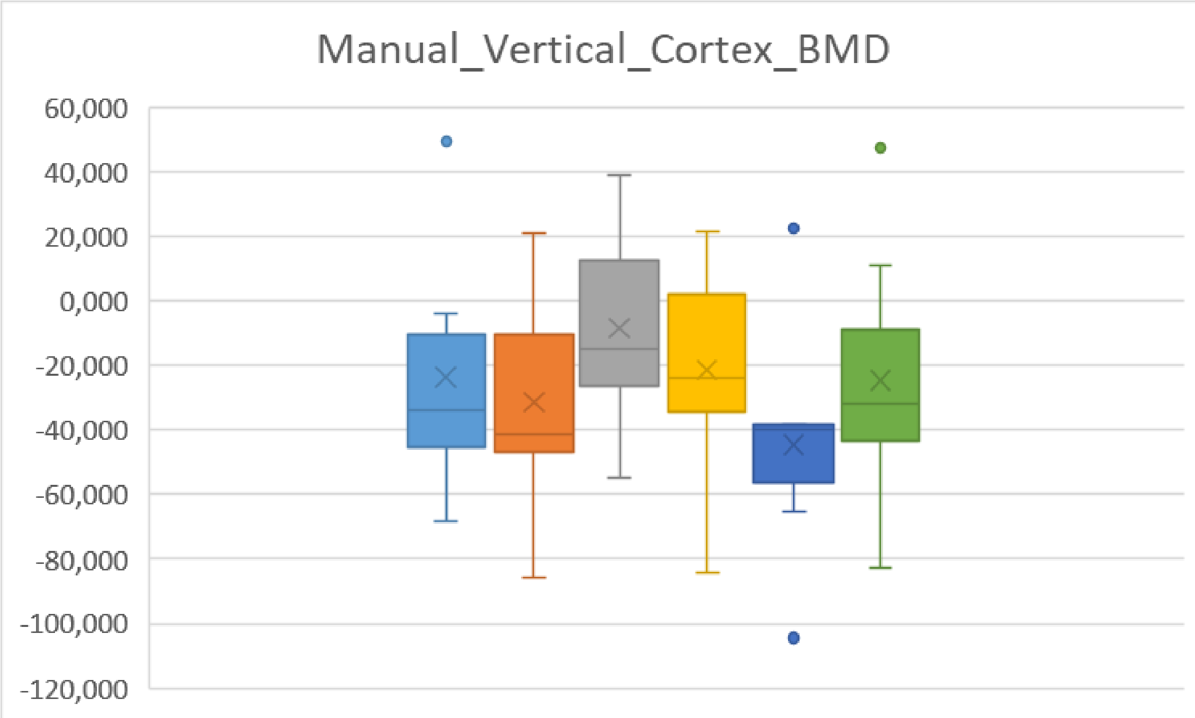


Figure 30: Compare Box-Plots of mesh and manual method for TV



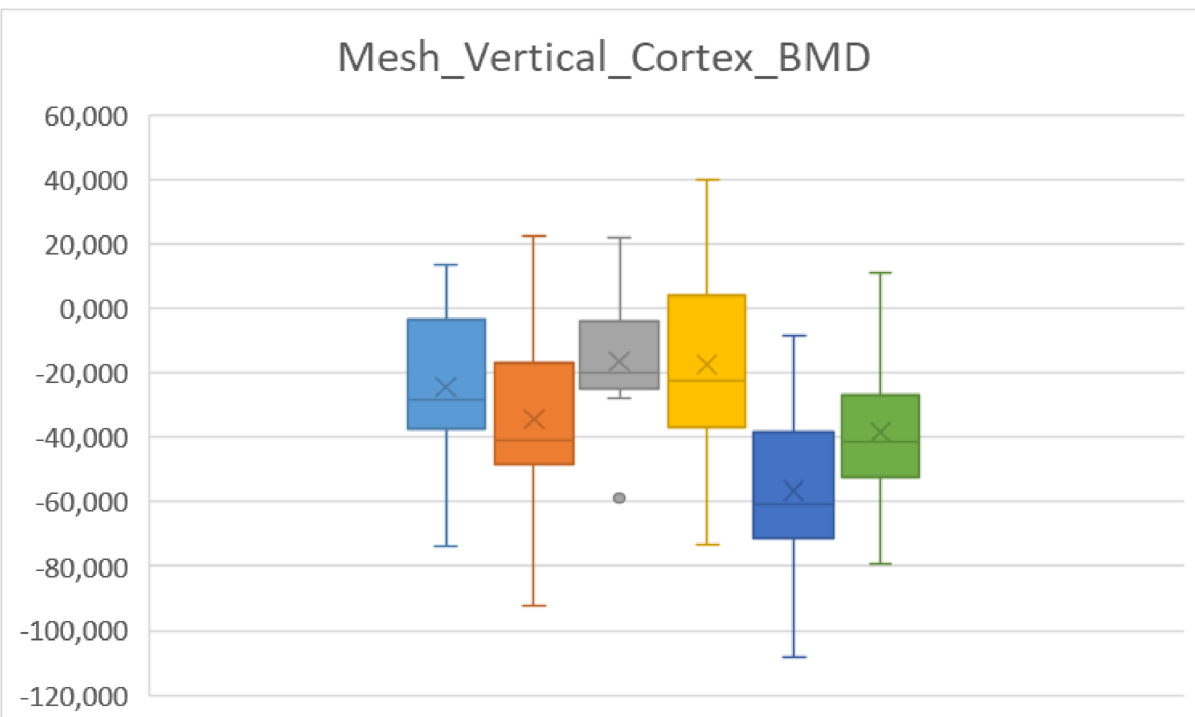


Figure 31: Compare Box-Plots of mesh and manual method for BMD

4. Analysis:

As can be seen in the results of all three methods (manual, mask registration and mesh registration) they all work very promising for every selected region and QCT parameter. Every analysis showed us that mesh registration method is similar to manual method. On the other hand, mask registration is usually having similar values for all vertebrae because it's just the mask mapping. The mesh registration showed good results for the focused region vertical cortex. The results were very close to the more time consuming manual method.

The possible reason for a different value in between methods is that different Ct-scanners have different configuration which can affect the QCT parameters. In this situation if we have the same vertebra which were scanned on different Ct-scanners. In different scanners the same vertebra has different position. Density at the boundary of vertebra affects the values of weighted cortical thickness. CT-scanner resolution has an effect on the cortical thickness of bone and different CT-scanners can have different resolution settings. It will also affect the standard deviation of the cortical thickness.

According to the hypothesis of this experiment which is registration of the ridge line using automatic segmentation for same vertebra in different CT-scanners. We can say that it's possible to register the ridge line in between vertebra which scanned on different CT-scanners but the specimen has to be same for all CT-scanners. In this case it's possible otherwise it will not satisfy the hypothesis.

To make results more accurate we can use image processing methods. Machine learning techniques such as convolutional neural networks can be helpful for this problem. This method can adapt the image structure more perfectly than image registration method. It learns the structure, boundary, content and many more things from the image by applying different filters and neural network parameters. It can help us to get perfect results in image segmentation.

5. Conclusion:

Automatic segmentation of a bone ridge line in between different CT-scanners using the same vertebra was checked in this project. Three different methods were performed to check if the hypothesis is true. All methods have different results but mesh and manual method seems to be close enough for our focused region vertical cortex specifically for cortical thickness, weighted cortical thickness and bone mineral density.

Mesh registration method can be performed in a specific situation where the same vertebrae which were scanned on different Ct-scanners. For other situation, this method will not work because manually segmented reference segmentation and mesh was needed to perform this method. Therefore, if in some situation where multiple scans for the same vertebra were not available so mesh registration method cannot be used.

In manual method, everything is performed manually with the help of in-house software "StructuralInsight". The results are perfectly accurate but it took a month of work to manually correct the segmentations and meshes of each vertebra for every center. In mesh registration all manual work had been done automatically. To perform mesh registration, we still need one reference center segmentations and meshes to map them to other vertebrae. In this project, registration results showed not significant differences to manual method results. It reduced our manual effort of minimum 4 hours per vertebra to three seconds. The statistical analysis results show that mesh registration method has slightly large or smaller QCT parameter values for some vertebrae than manual method. Which can prove that the statement is depend on CT-scanners and bone. Therefore it's satisfy the hypothesis that cross calibration of cortical bone parameters through CT-scans of embedded human vertebral bodies is possible using mesh registration method.

6. Acknowledgements:

I would first like to thank my supervisor, Prof. Dr. Claus-C Glüer for giving me an opportunity to do my master project in his department of radiology and neuroradiology. I would also like to thank my second supervisor, Prof. Dr. Hauke Schramm for allowing and supporting me to do my project outside of university.

Furthermore, I would like to acknowledge Mr. Jaime Pena for supporting me throughout the project. Your insightful understanding and feedback motivated me to bring my work to higher level and pushed me to sharpen my thinking.

I would also like to thank Mr. Timo Damm and Mr. Stefan Reinhold for their valuable technical support and feedback.

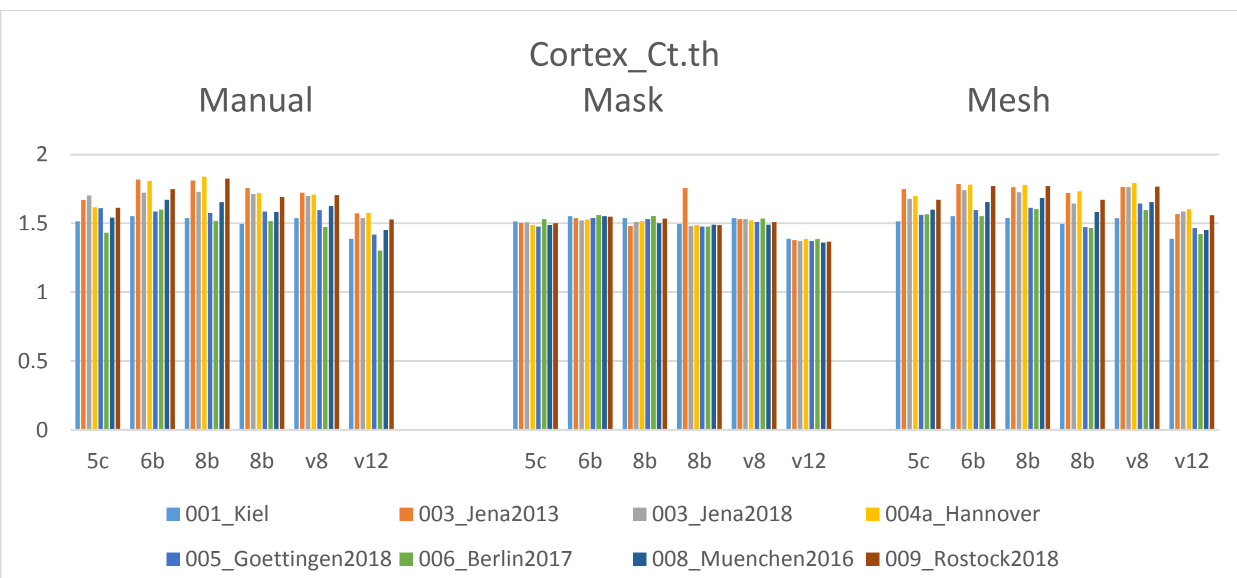
7. References:

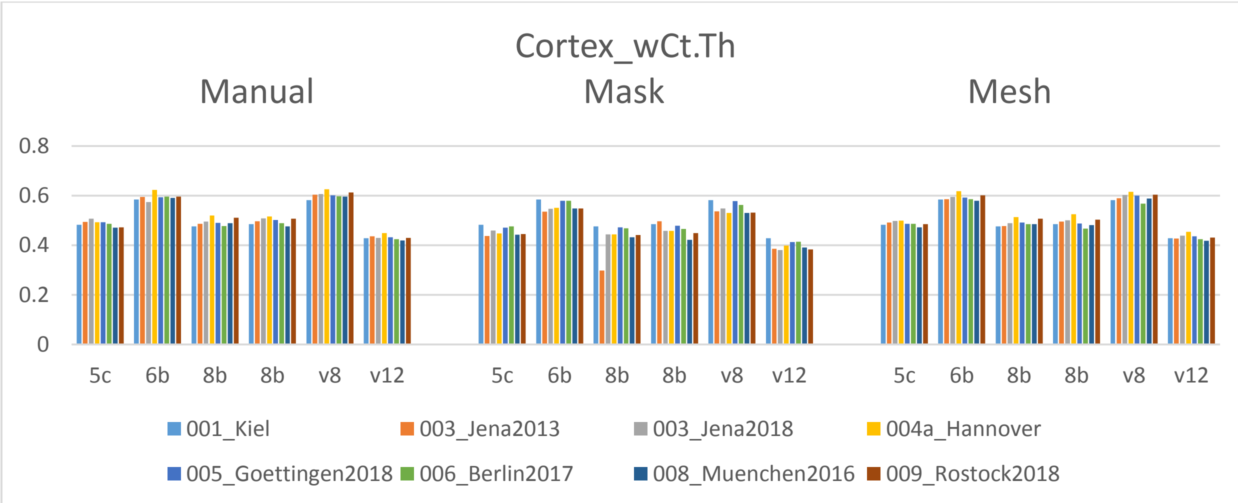
1. *Correcting image rotation*. (2020). Bruker.Com. https://www.bruker.com/products/microtomography/academy/correcting-image-rotation.html#:%7E:text=Alignment%20is%20a%20complex%20issue,3D%20space%20during%20the%20scan.&text=In%20a%20perfectly%20aligned%20scan,the%20midline%20of%20the%20camera.
2. *Approaches to Registering Images - MATLAB & Simulink*. (2020). Mathworks. https://www.mathworks.com/help/images/approaches-to-registering-images.html#:%7E:text=Image%20registration%20is%20the%20process,they%20align%20with%20the%20reference.

8. Appendix A

- **Cortex:**

	ManualSeg					RegMask					RegMesh				
CenterID	Ct.Th	wCt.Th	Ct.Th-SD	TV	BMD	Ct.Th	wCt.Th	Ct.Th-SD	TV	BMD	Ct.Th	wCt.Th	Ct.Th-SD	TV	BMD
001_Kiel2018	1.504	0.507	0.439	7.347	415.929	1.504	0.507	0.439	7.347	415.929	1.504	0.507	0.439	7.347	415.929
003_Jena2013	1.725	0.519	0.492	8.162	369.248	1.532	0.449	0.445	7.131	360.601	1.725	0.511	0.477	8.115	364.460
003_Jena2018	1.685	0.521	0.472	7.864	380.139	1.487	0.473	0.441	7.352	390.371	1.690	0.521	0.477	7.890	379.868
004_Hannover2018	1.711	0.538	0.461	8.174	383.404	1.487	0.472	0.442	7.360	390.021	1.731	0.538	0.482	8.153	380.318
005_Goettingen2018	1.562	0.519	0.475	7.331	409.977	1.484	0.499	0.439	7.348	414.170	1.559	0.516	0.467	7.249	410.422
006_Berlin2015	1.474	0.512	0.427	6.821	428.518	1.507	0.495	0.437	7.311	405.041	1.534	0.503	0.475	6.954	410.843
008_Muenchen2016	1.588	0.507	0.416	7.852	380.986	1.480	0.461	0.447	7.201	381.059	1.606	0.504	0.427	7.724	377.309
009_Rostock2018	1.685	0.522	0.459	8.005	377.147	1.490	0.467	0.440	7.350	384.435	1.702	0.522	0.459	7.972	374.002
Overall Mean	1.617	0.518	0.455	7.694	393.168	1.496	0.478	0.441	7.300	392.703	1.631	0.515	0.463	7.676	389.144
Overall Standard Dev	0.098	0.010	0.026	0.480	21.688	0.017	0.020	0.004	0.086	18.515	0.092	0.012	0.020	0.442	19.941

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0.4
0.2
0
5c
6b
8b
8b
v8
v12
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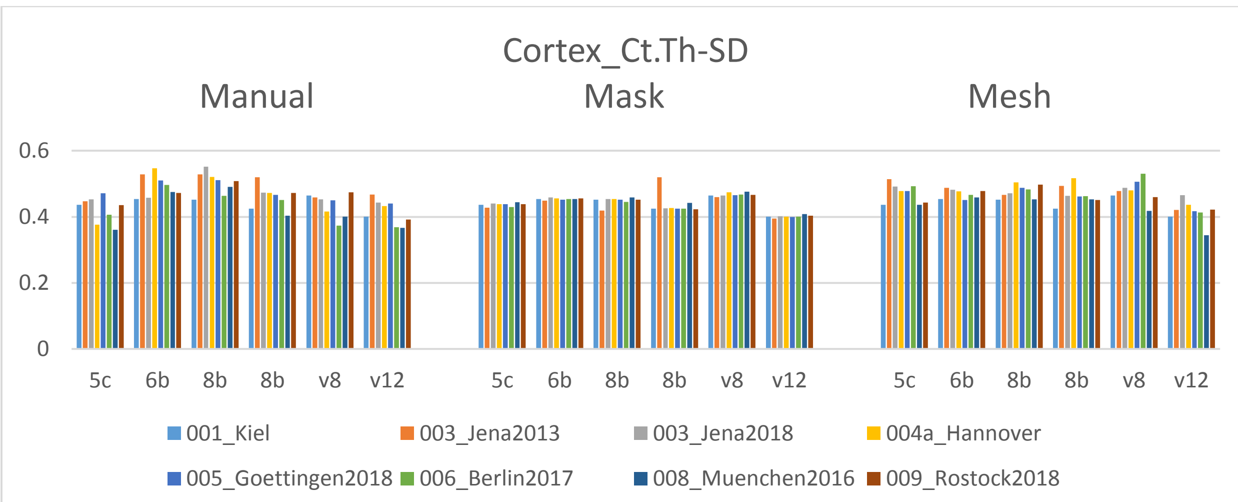
003_Jena2013
003_Jena2018
004a_Hannover
005_Goettingen2018
006_Berlin2017
008_Muenchen2016
009_Rostock2018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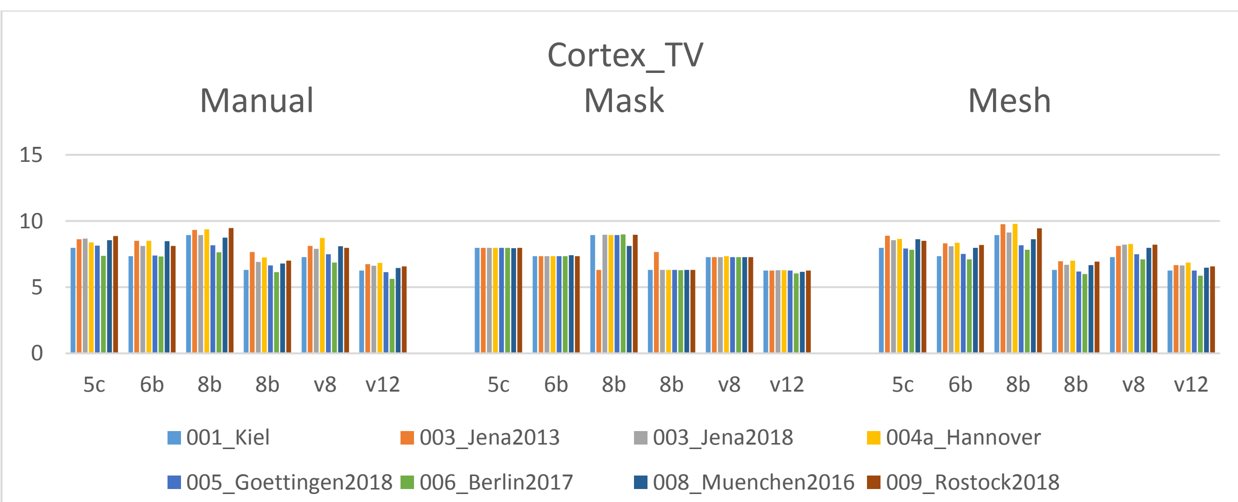
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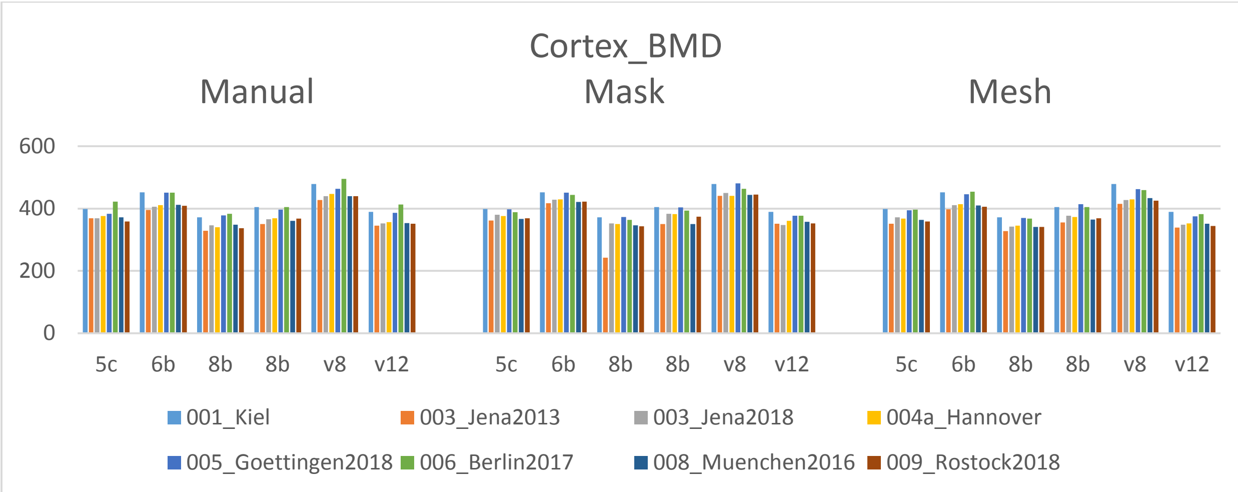

- **Lower_Enaplate:**

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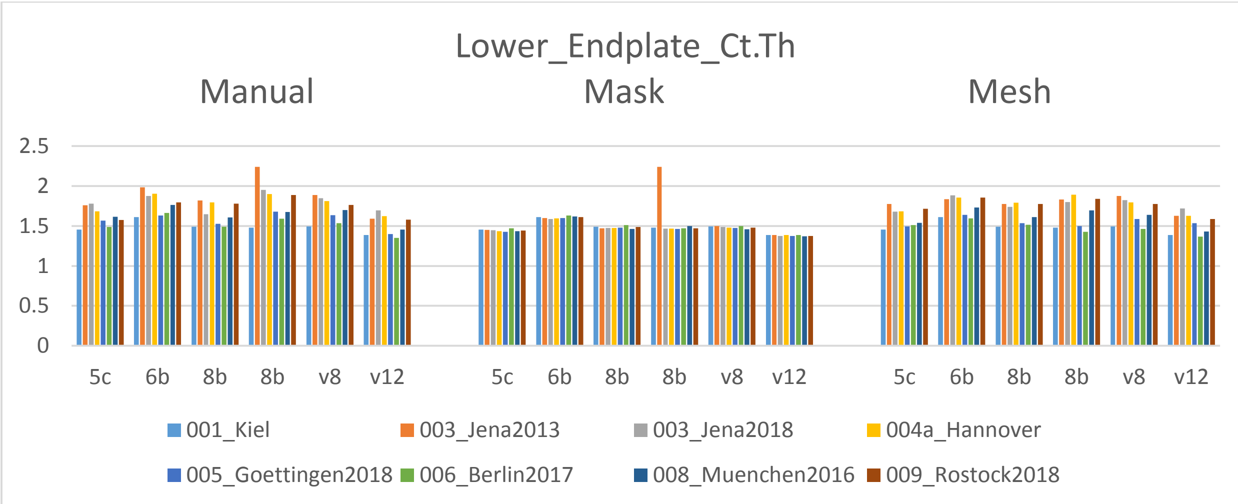
001_Kiel2018	1.486	0.521	0.376	2.295	417.087	1.486	0.521	0.376	2.295	417.087	1.486	0.521	0.376	2.295	417.087
003_Jena2013	1.881	0.564	0.420	3.007	360.251	1.608	0.468	0.381	2.267	354.674	1.787	0.540	0.371	2.856	358.020
003_Jena2018	1.800	0.557	0.370	2.752	369.721	1.473	0.480	0.375	2.295	385.910	1.774	0.556	0.374	2.737	374.129
004_Hannover2018	1.786	0.574	0.370	2.722	379.235	1.473	0.493	0.375	2.295	396.544	1.774	0.572	0.366	2.764	381.076
005_Goettingen2018	1.573	0.538	0.402	2.374	403.513	1.469	0.504	0.375	2.295	406.463	1.548	0.530	0.371	2.439	407.556
006_Berlin2015	1.521	0.531	0.359	2.244	415.803	1.495	0.520	0.363	2.293	413.903	1.480	0.517	0.360	2.225	417.764
008_Muenchen2016	1.636	0.555	0.394	2.559	396.919	1.473	0.500	0.398	2.452	404.396	1.609	0.543	0.378	2.562	396.331
009_Rostock2018	1.731	0.550	0.390	2.637	375.923	1.477	0.488	0.377	2.295	391.395	1.758	0.560	0.360	2.686	376.454
Overall Mean	1.677	0.549	0.385	2.574	389.807	1.494	0.497	0.378	2.311	396.297	1.652	0.542	0.369	2.571	391.052
Overall Standard Dev	0.144	0.018	0.020	0.260	21.514	0.047	0.018	0.010	0.058	19.913	0.136	0.019	0.007	0.231	21.980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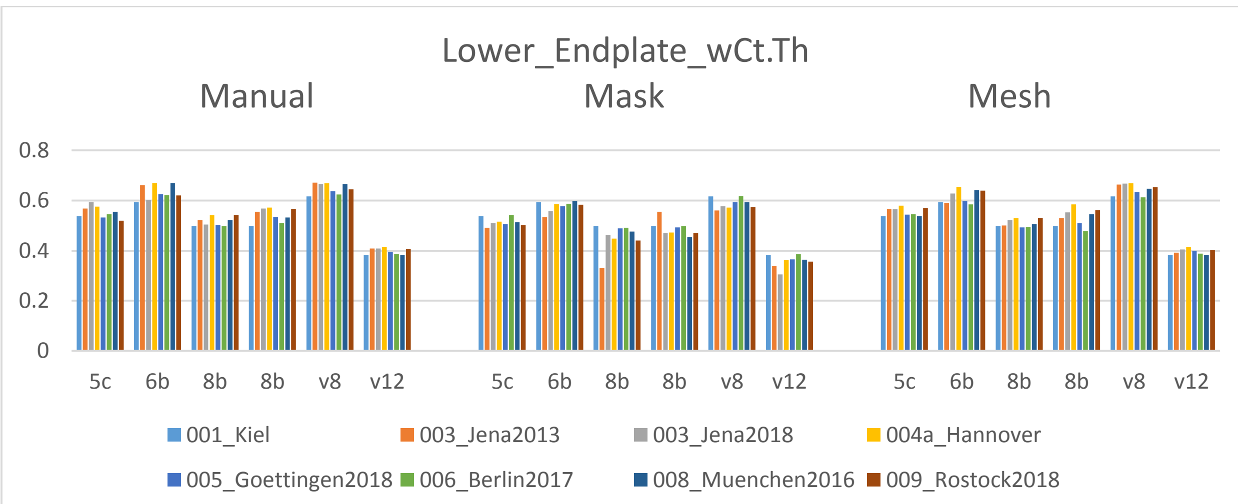
003_Jena2018
004a_Hannover
005_Goettingen2018
006_Berlin2017
008_Muenchen2016
009_Rostock2018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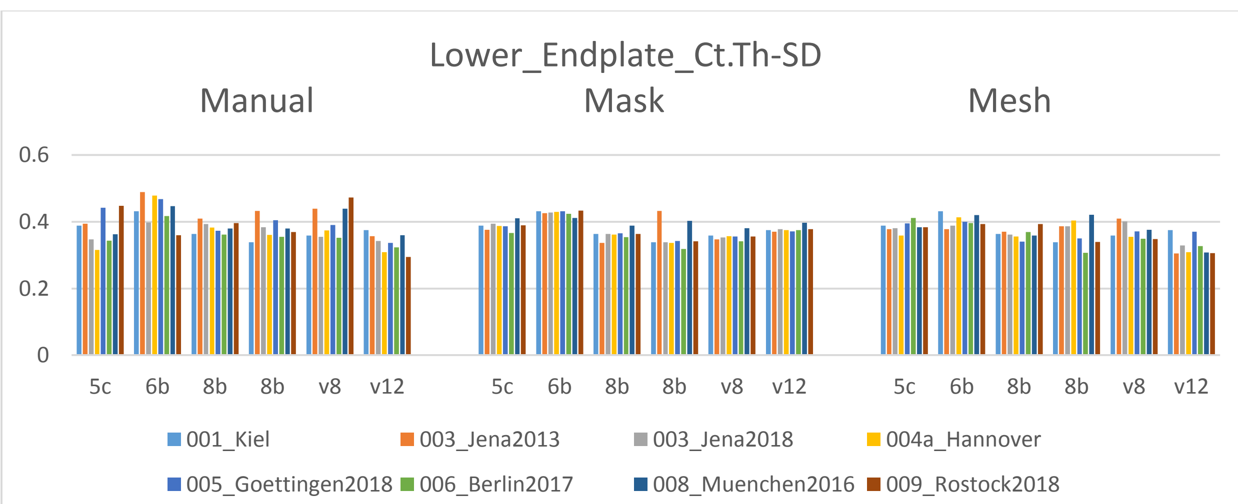
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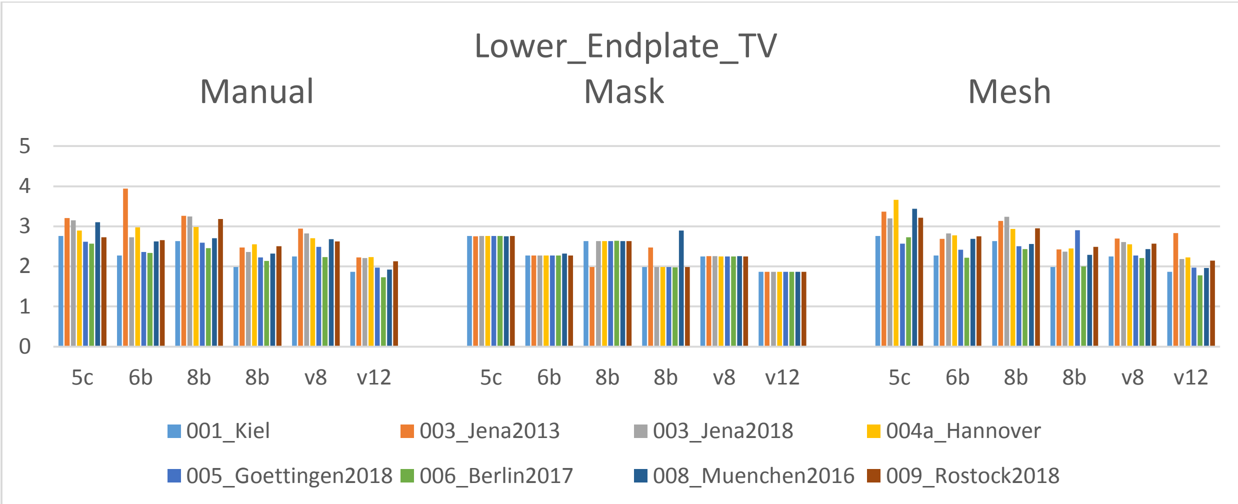
009_Rostock2018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1
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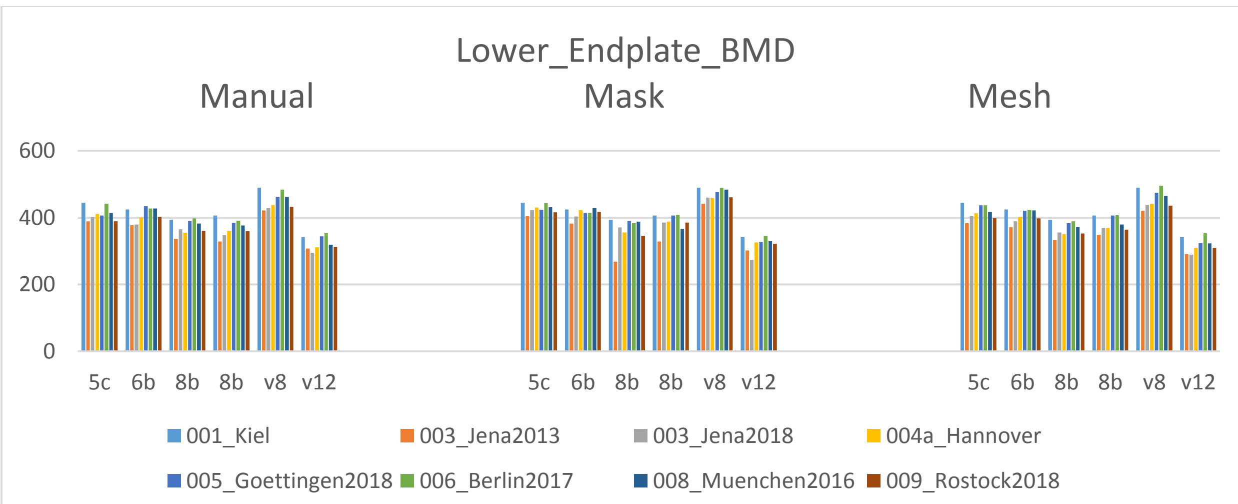
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Mesh
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200
0
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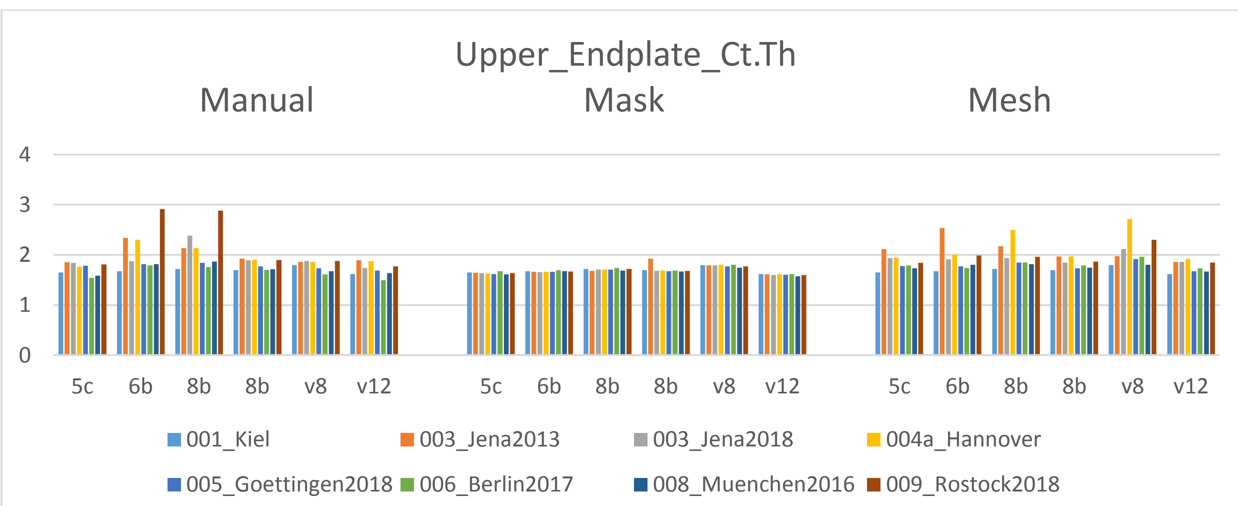
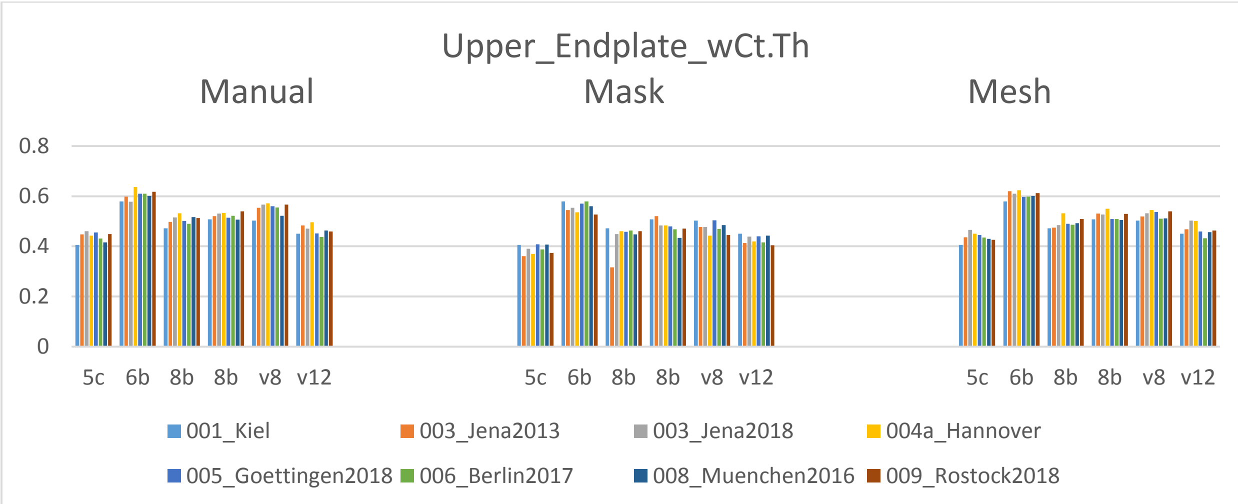
001_Kiel
003_Jena2013
003_Jena2018
004a_Hannover
005_Goettingen2018
006_Berlin2017
008_Muenchen2016
009_Rostock2018

- **Upper_Endplate:**

	ManualSeg					RegMask					RegMesh				
CenterID	Ct.Th	wCt.Th	Ct.Th-SD	TV	BMD	Ct.Th	wCt.Th	Ct.Th-SD	TV	BMD	Ct.Th	wCt.Th	Ct.Th-SD	TV	BMD
001_Kiel2018	1.691	0.486	0.440	2.341	347.026	1.691	0.486	0.440	2.341	347.026	1.691	0.486	0.440	2.341	347.026
003_Jena2013	2.000	0.517	0.403	2.835	316.422	1.719	0.439	0.416	2.298	308.654	2.104	0.508	0.427	2.806	305.938
003_Jena2018	1.934	0.521	0.413	2.721	332.002	1.678	0.465	0.440	2.341	334.332	1.933	0.520	0.427	2.924	325.919
004_Hannover2018	1.971	0.536	0.406	2.782	330.408	1.683	0.452	0.440	2.349	323.623	2.174	0.534	0.456	2.764	320.782
005_Goettingen2018	1.771	0.515	0.477	2.758	350.512	1.672	0.477	0.440	2.341	343.467	1.787	0.506	0.469	2.637	342.794
006_Berlin2015	1.649	0.508	0.415	2.463	368.237	1.702	0.464	0.440	2.339	328.768	1.808	0.495	0.462	2.466	332.182
008_Muenchen2016	1.716	0.504	0.416	2.612	346.011	1.659	0.463	0.455	2.341	337.724	1.761	0.500	0.441	2.551	336.665
009_Rostock2018	2.192	0.524	0.414	2.759	326.608	1.680	0.447	0.439	2.342	320.124	1.966	0.513	0.426	2.737	317.930
Overall Mean	1.866	0.514	0.423	2.659	339.653	1.685	0.462	0.439	2.337	330.465	1.903	0.508	0.443	2.653	328.654
Overall Standard Dev	0.189	0.015	0.024	0.174	16.404	0.018	0.016	0.011	0.016	12.780	0.172	0.015	0.017	0.193	13.704




Upper_Endplate_wCt.Th
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Mask
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0.2
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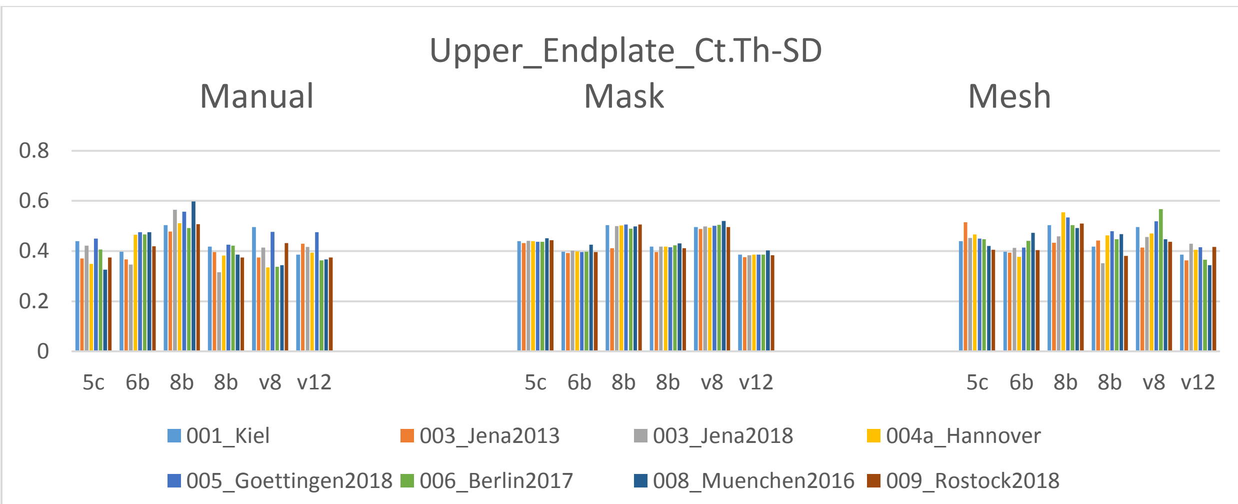
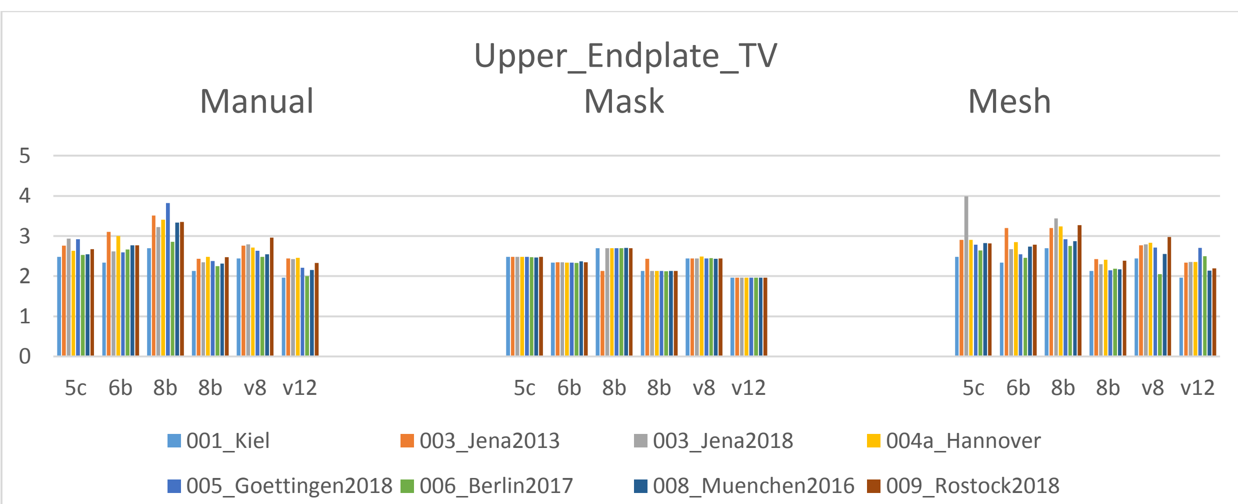
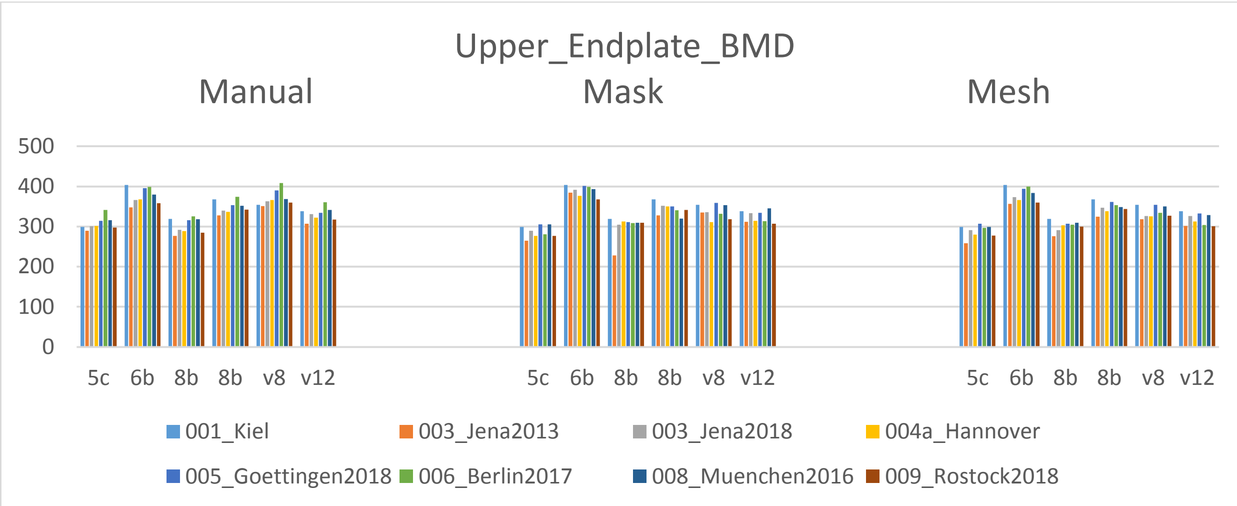
5c 6b 8b 8b v8 v12
5c 6b 8b 8b v8 v12
5c 6b 8b 8b v8 v12
001_Kiel
003_Jena2013
003_Jena2018
004a_Hannover
005_Goettingen2018
006_Berlin2017
008_Muenchen2016
009_Rostock2018

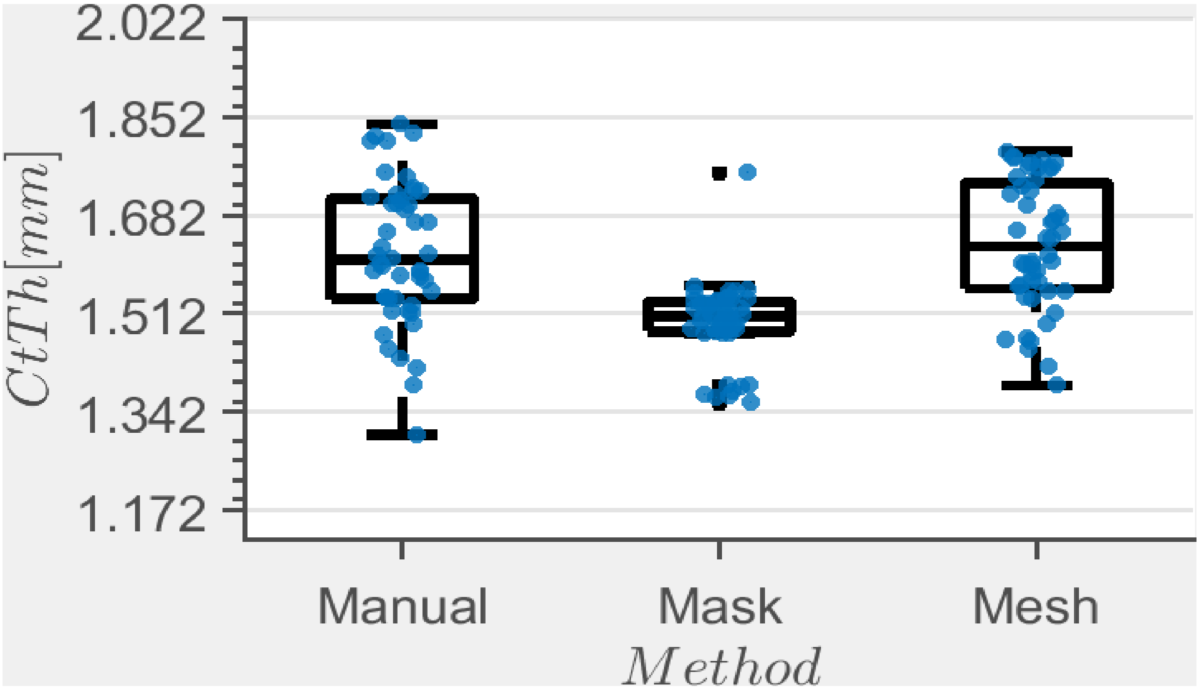

Upper_Endplate_Ct.Th-SD
Manual
Mask
Mesh
0.8
0.6
0.4
0.2
0
5c 6b 8b 8b v8 v12
5c 6b 8b 8b v8 v12
5c 6b 8b 8b v8 v12
001_Kiel
003_Jena2013
003_Jena2018
004a_Hannover
005_Goettingen2018
006_Berlin2017
008_Muenchen2016
009_Rostock2018

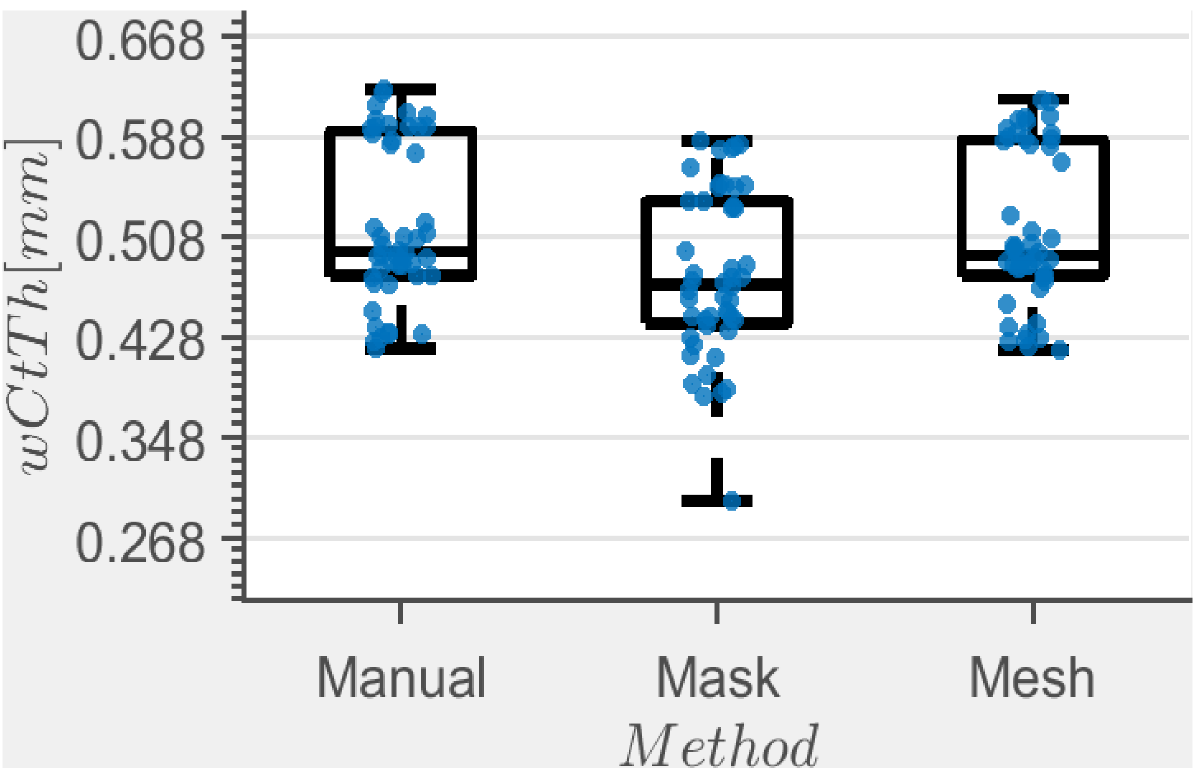

Upper_Endplate_TV
Manual
Mask
Mesh
5
4
3
2
1
0
5c 6b 8b 8b v8 v12
5c 6b 8b 8b v8 v12
5c 6b 8b 8b v8 v12
001_Kiel
003_Jena2013
003_Jena2018
004a_Hannover
005_Goettingen2018
006_Berlin2017
008_Muenchen2016
009_Rostock2018

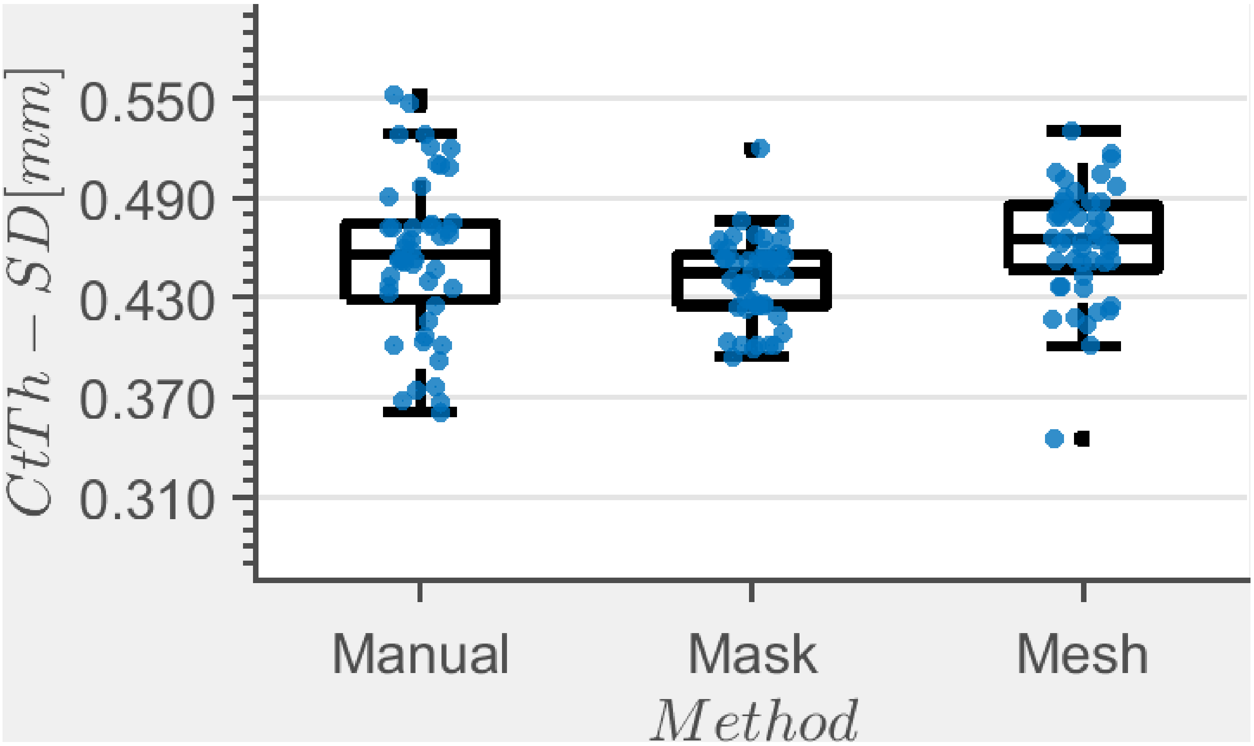

Upper_Endplate_BMD
Manual
Mask
Mesh
500
400
300
200
100
0
5c 6b 8b 8b v8 v12
5c 6b 8b 8b v8 v12
5c 6b 8b 8b v8 v12
001_Kiel
003_Jena2013
003_Jena2018
004a_Hannover
005_Goettingen2018
006_Berlin2017
008_Muenchen2016
009_Rostock2018

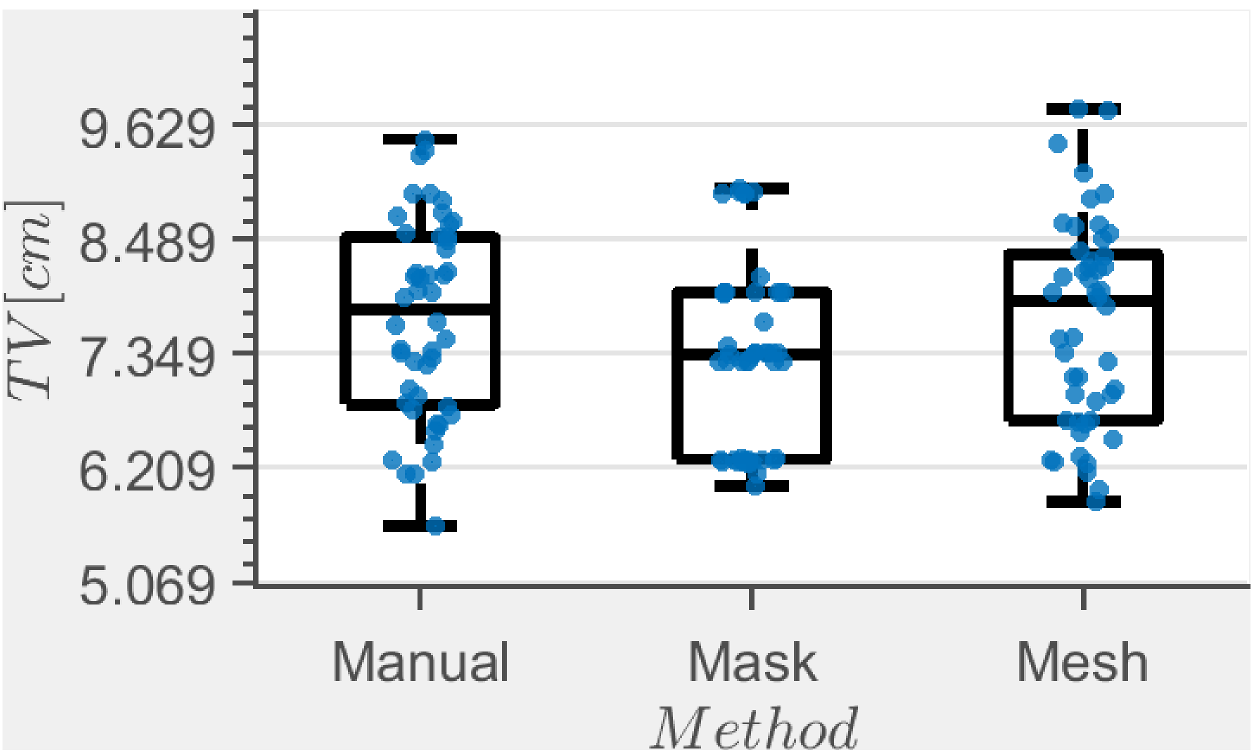
9. Appendix B

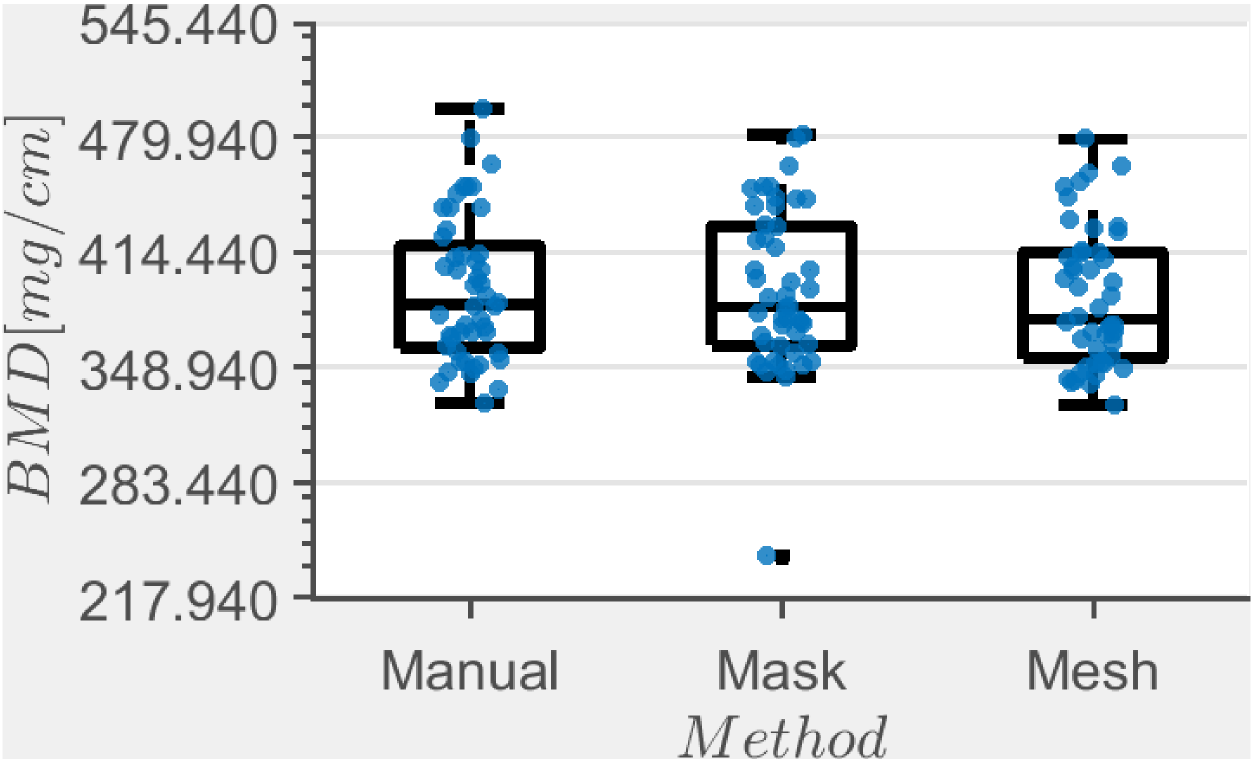
- **Cortex:**



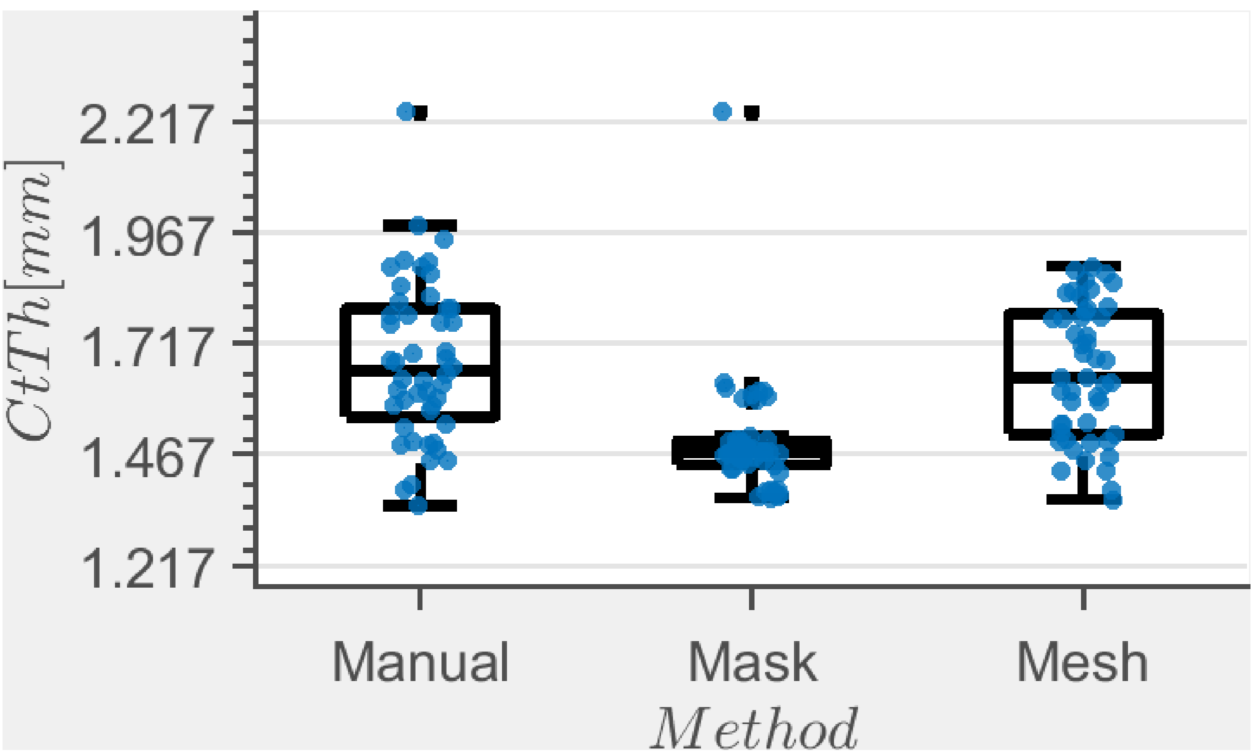


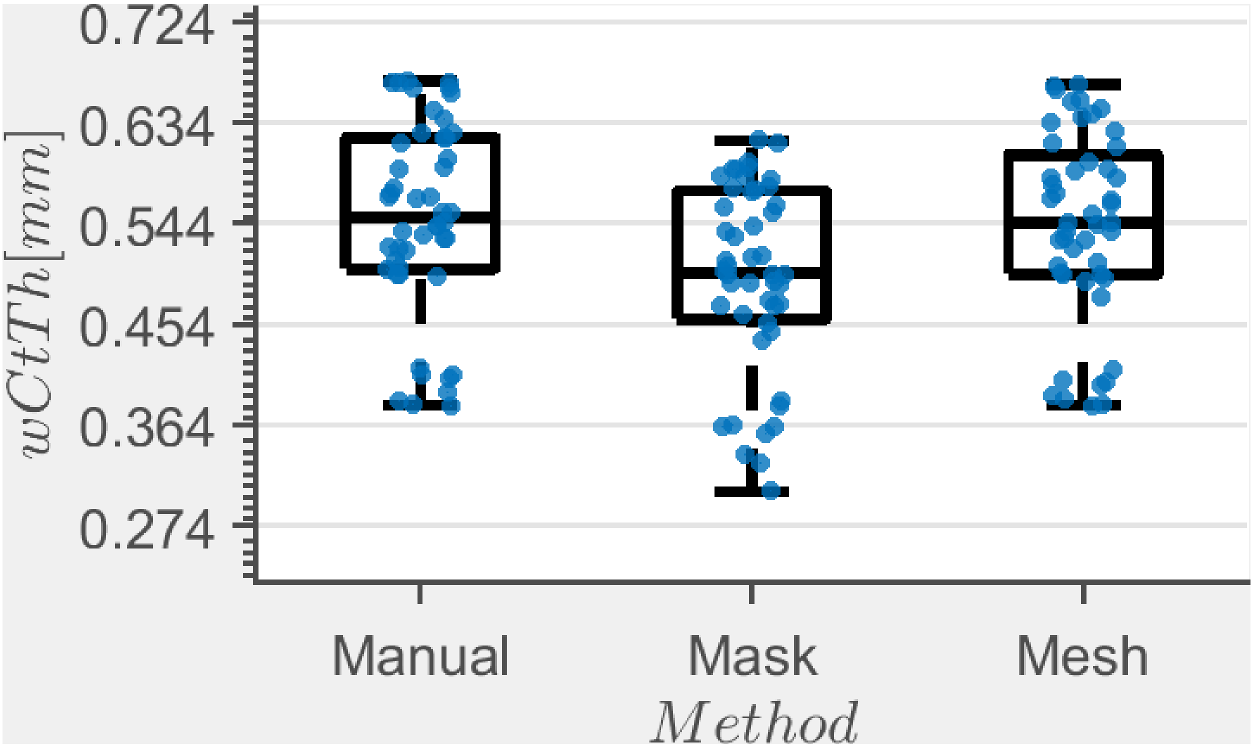

$CtTh-SD[mm]$
0.550
0.490
0.430
0.370
0.310
Manual
Mask
Mesh
$Method$

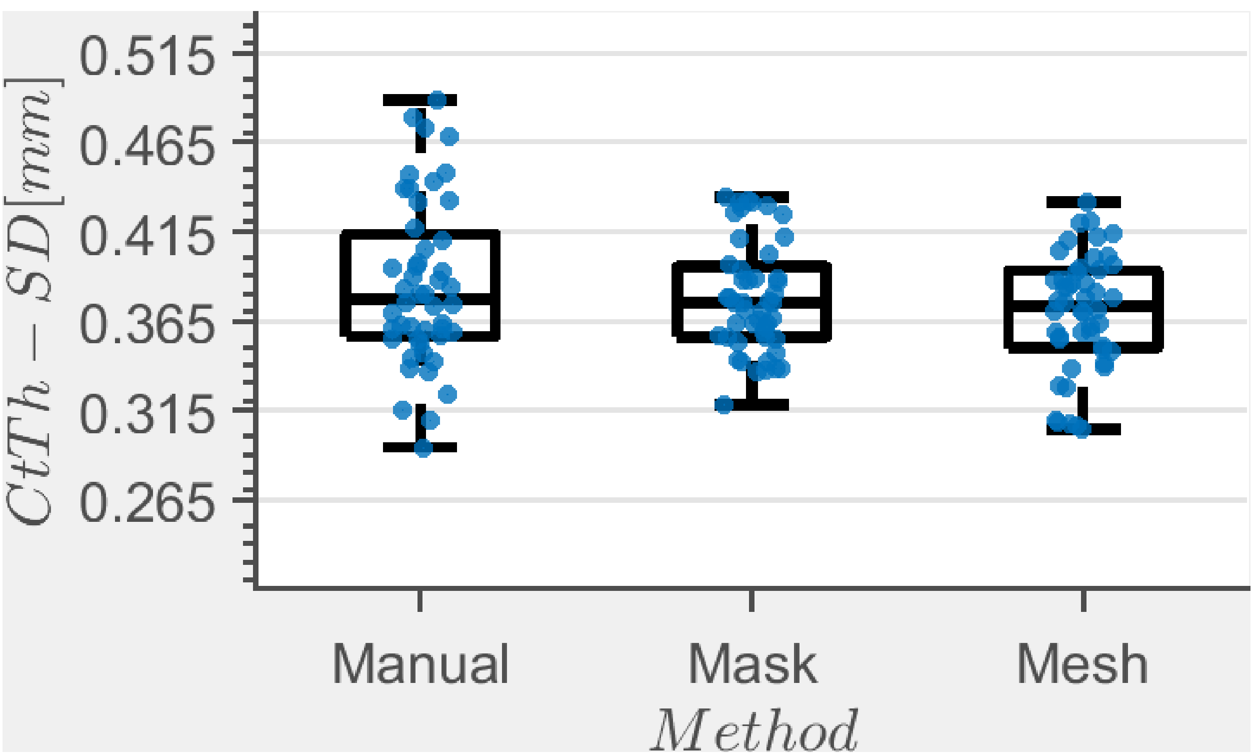

$TV[cm]$
9.629
8.489
7.349
6.209
5.069
Manual
Mask
Mesh
$Method$

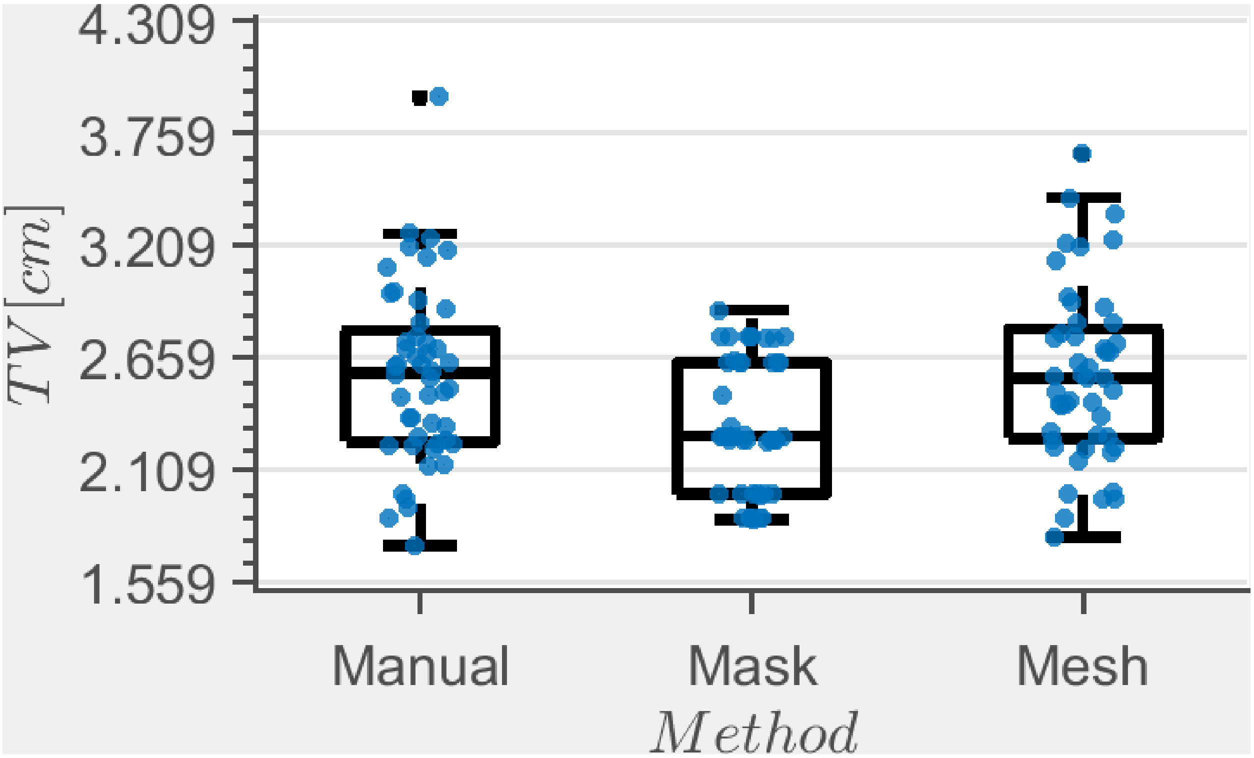


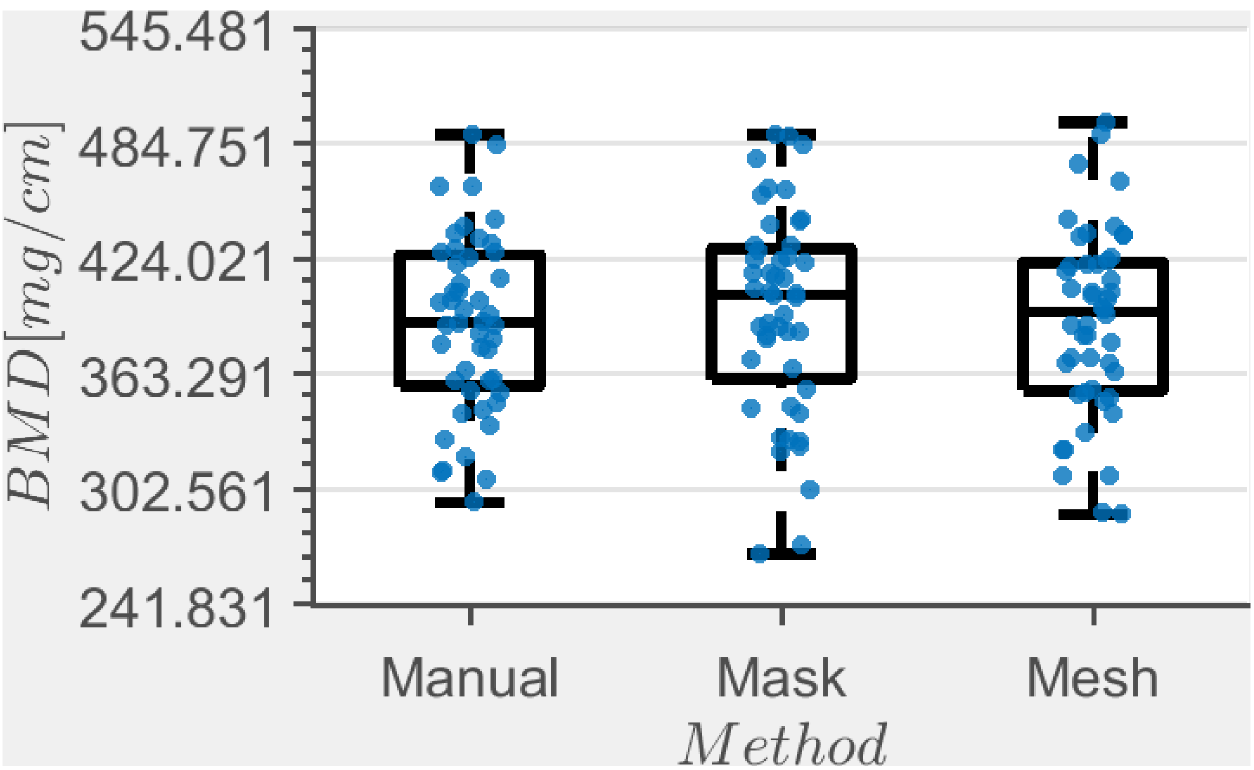
- **Lower_Endplate:**



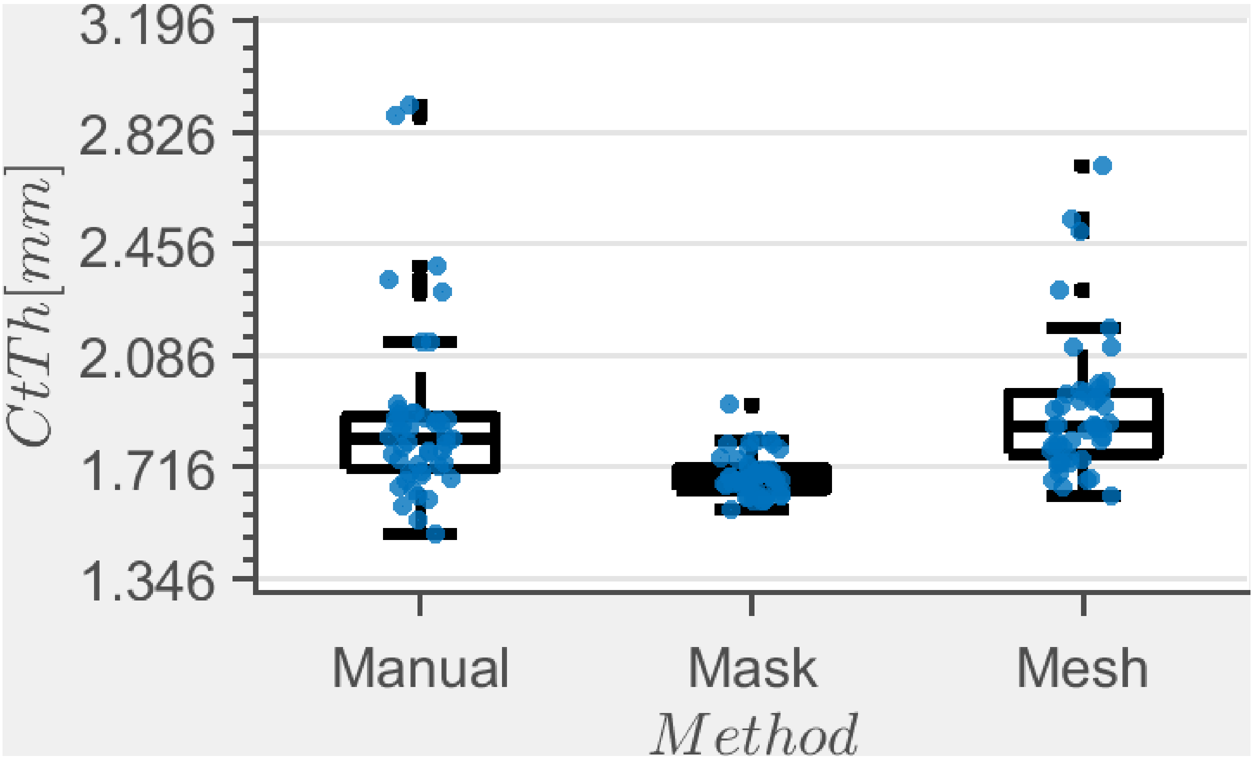

0.724
0.634
0.544
0.454
0.364
0.274
$wCtTh[mm]$
Manual
Mask
Mesh
$Method$

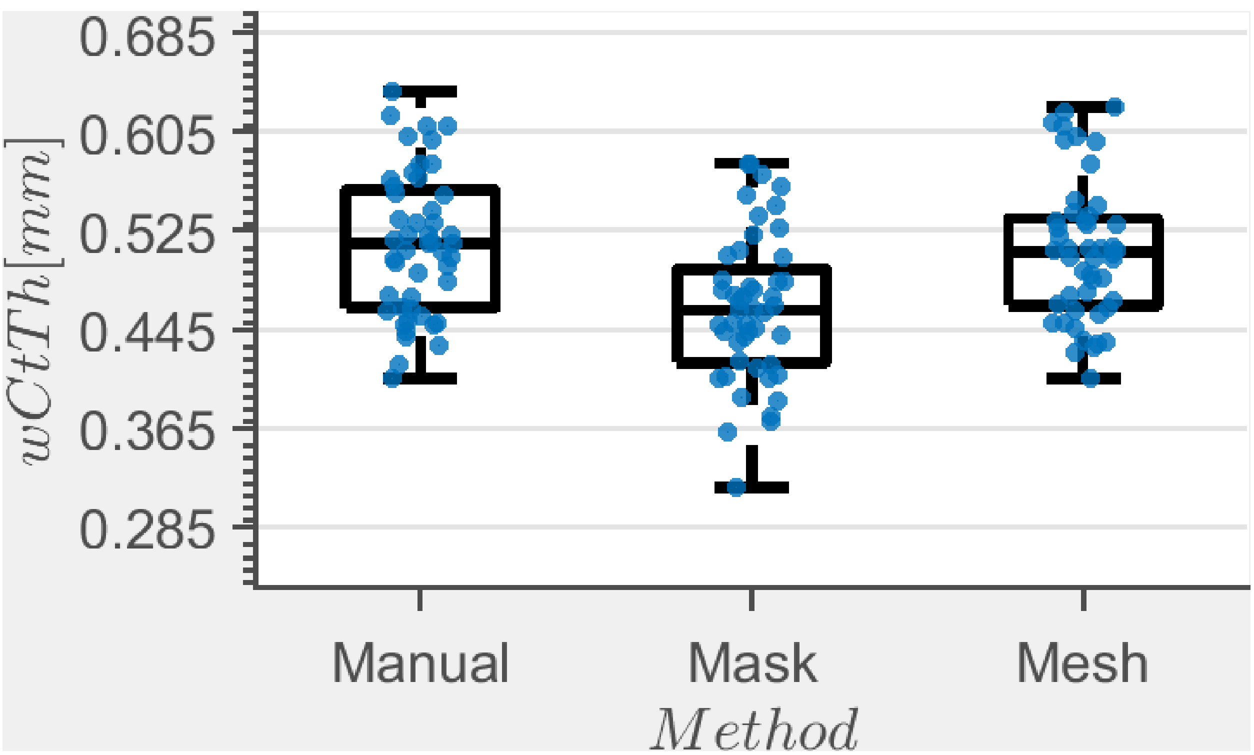

0.515
0.465
0.415
0.365
0.315
0.265
$CtTh - SD[mm]$
Manual
Mask
Mesh
$Method$

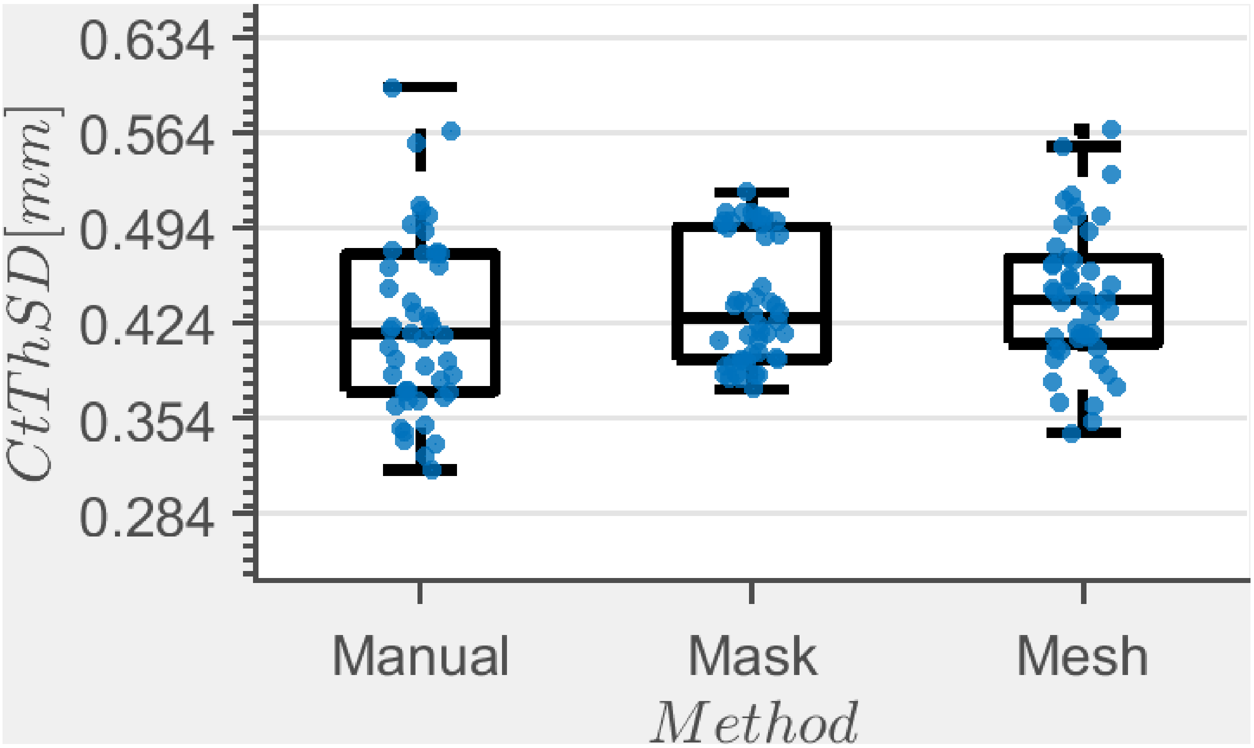

4.309
3.759
3.209
2.659
2.109
1.559
$TV[cm]$
Manual
Mask
Mesh
$Method$

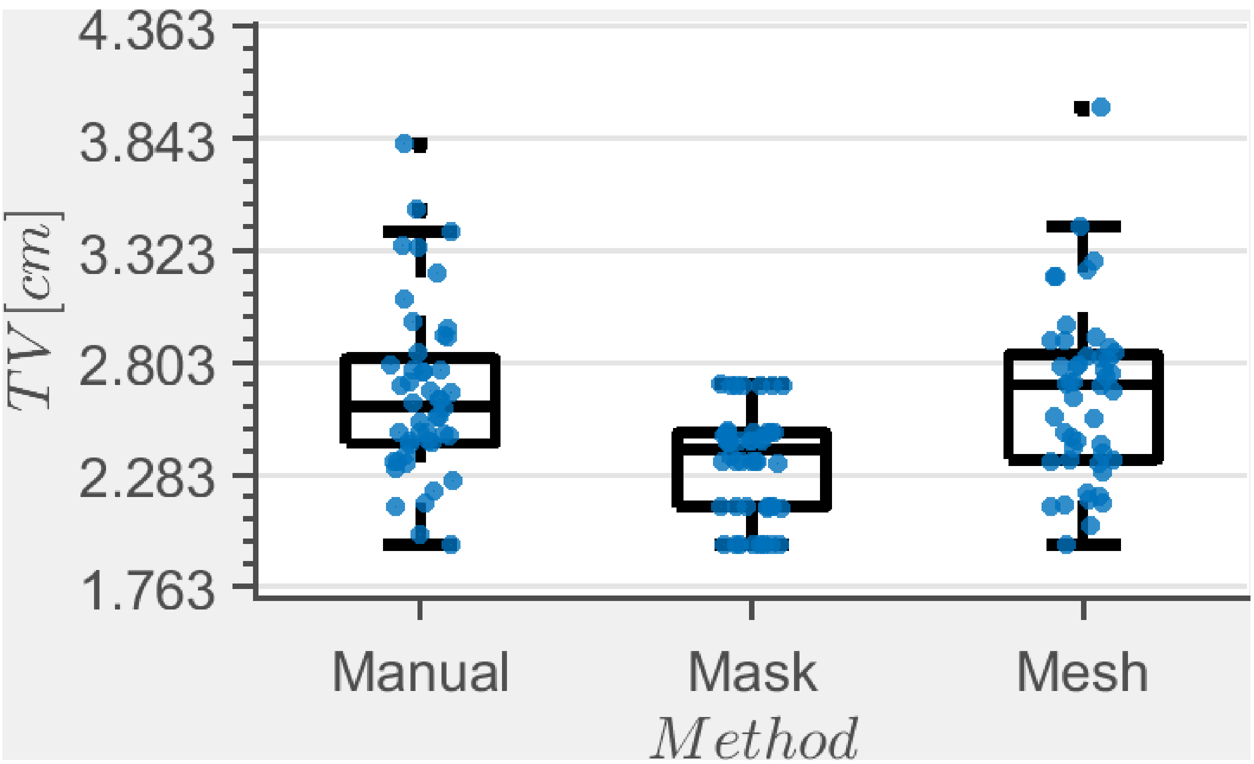

545.481
484.751
424.021
363.291
302.561
241.831
$BMD[mg/cm]$
Manual
Mask
Mesh
$Method$

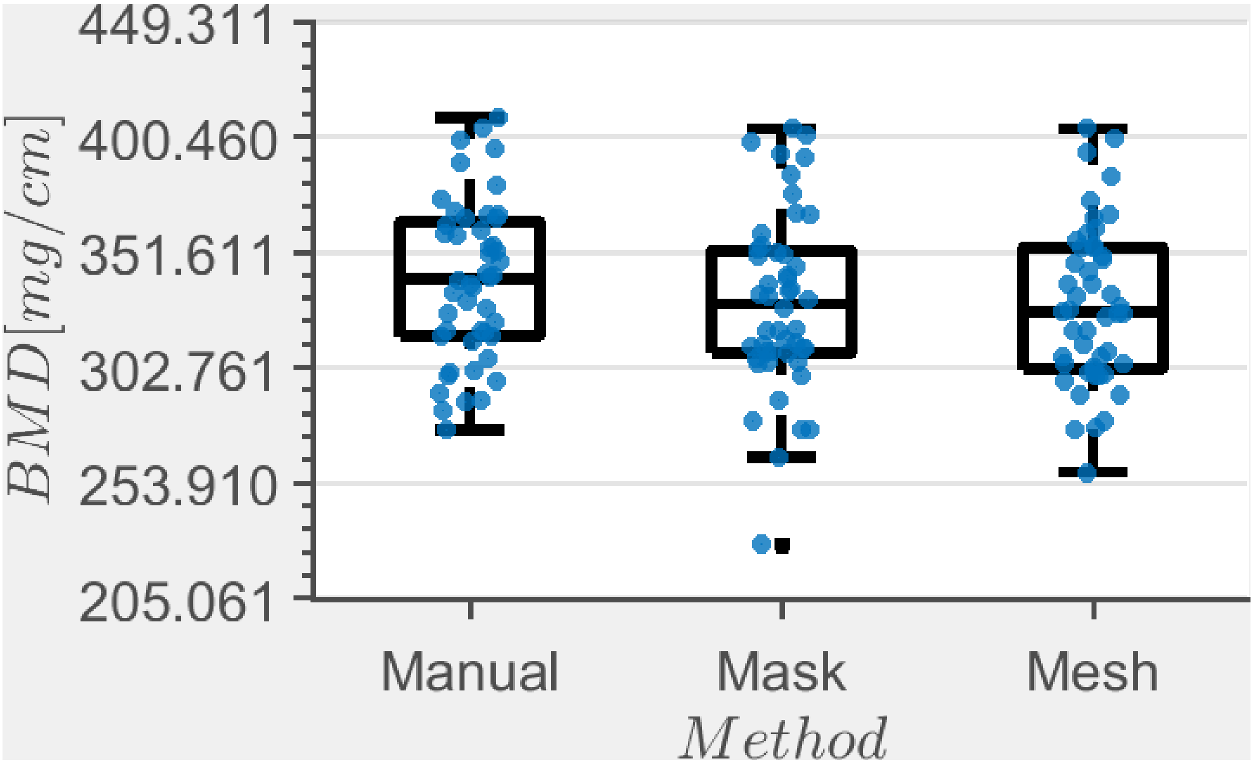
- **Upper_Endplate:**






0.634
0.564
0.494
0.424
0.354
0.284
$CtThSD[mm]$
Manual
Mask
Mesh
$Method$

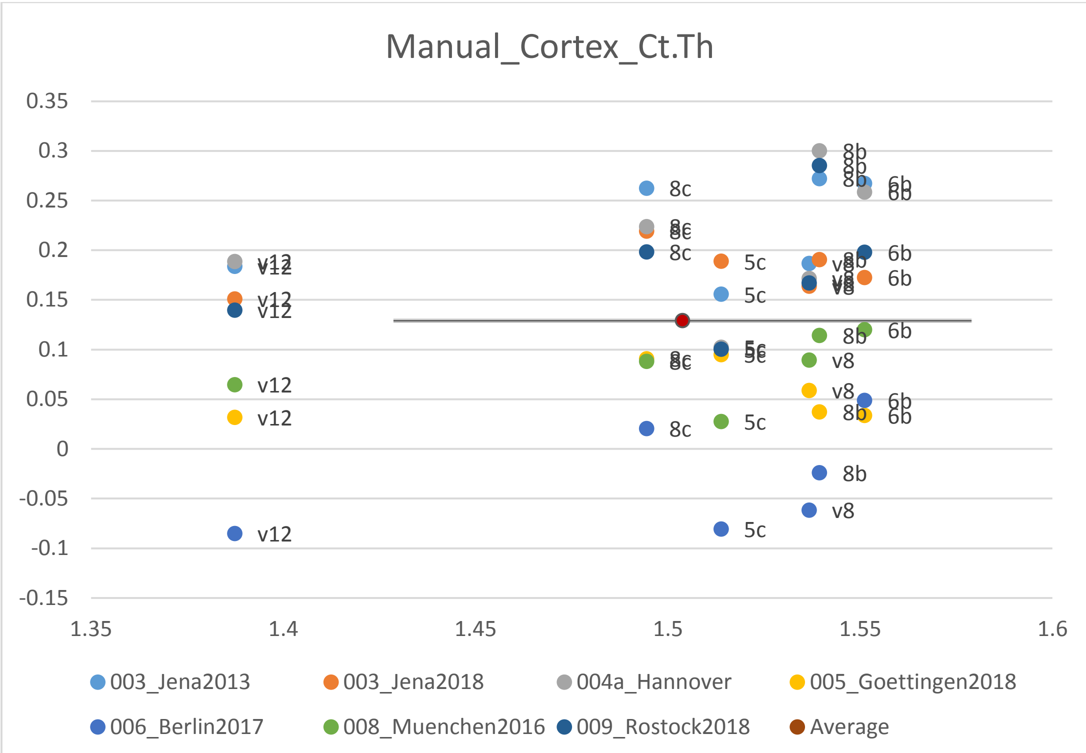

4.363
3.843
3.323
2.803
2.283
1.763
$TV[cm]$
Manual
Mask
Mesh
$Method$

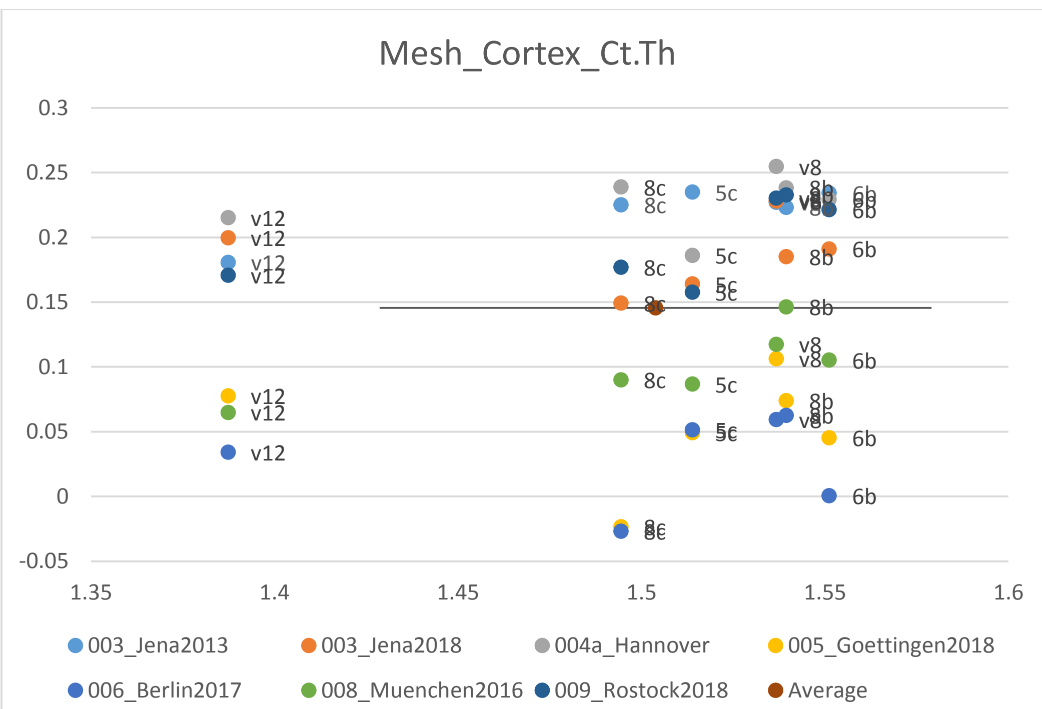

449.311
400.460
351.611
302.761
253.910
205.061
$BMD[mg/cm]$
Manual
Mask
Mesh
$Method$

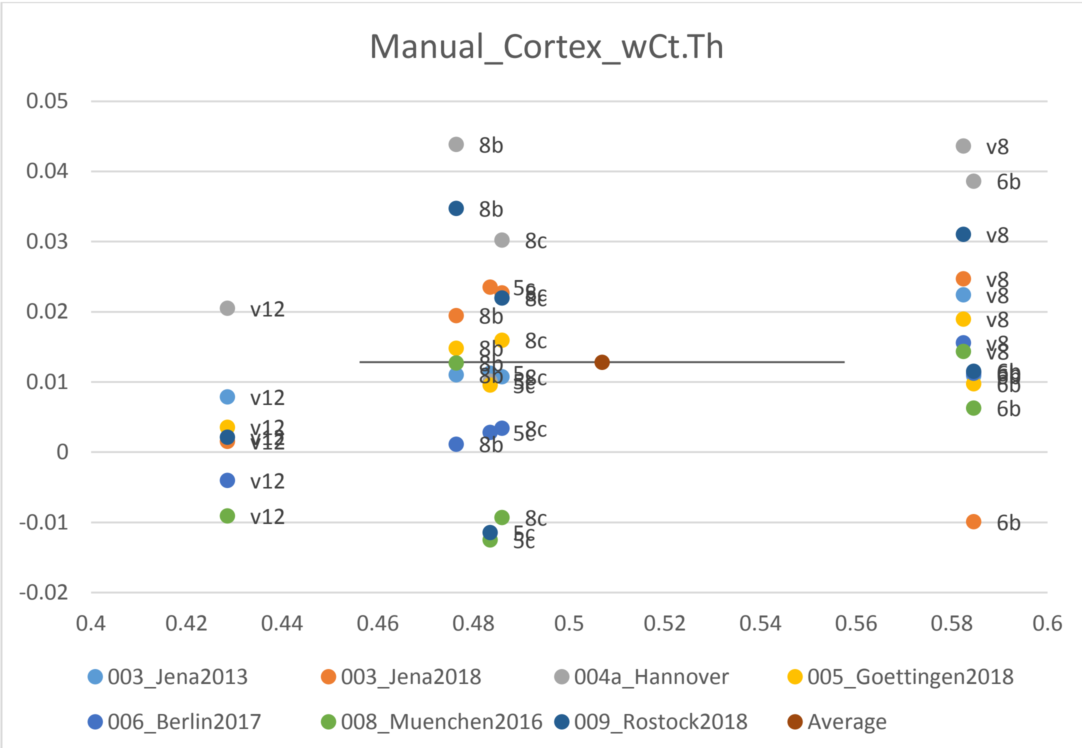
10. Appendix C

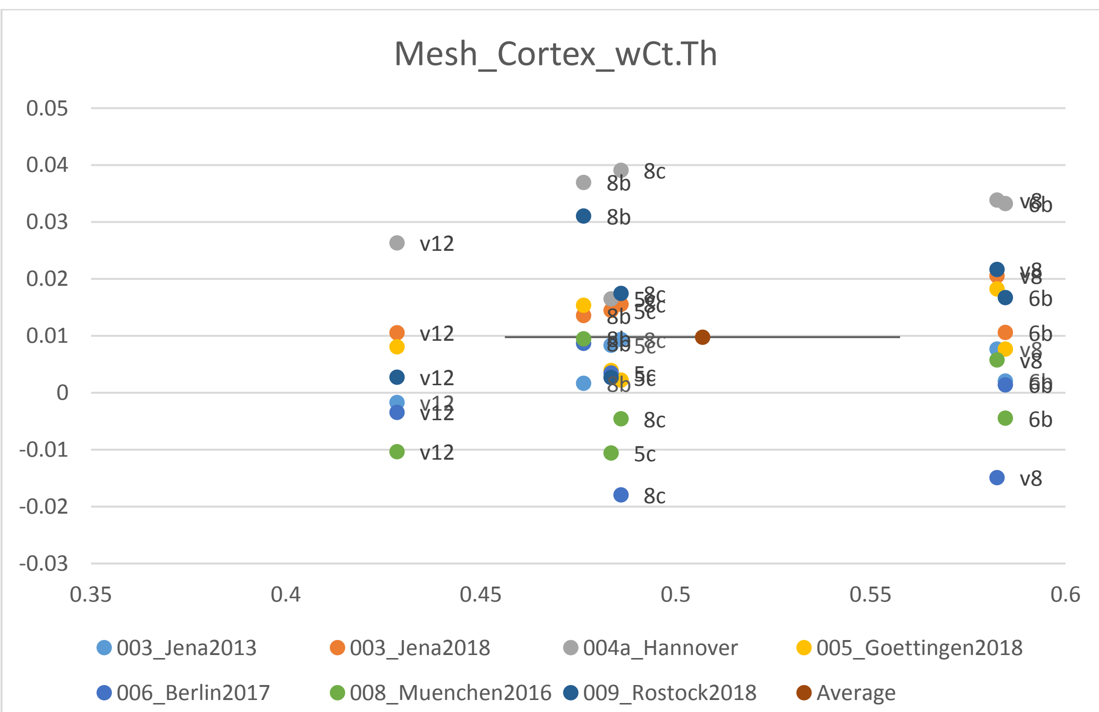
- **Cortex:**

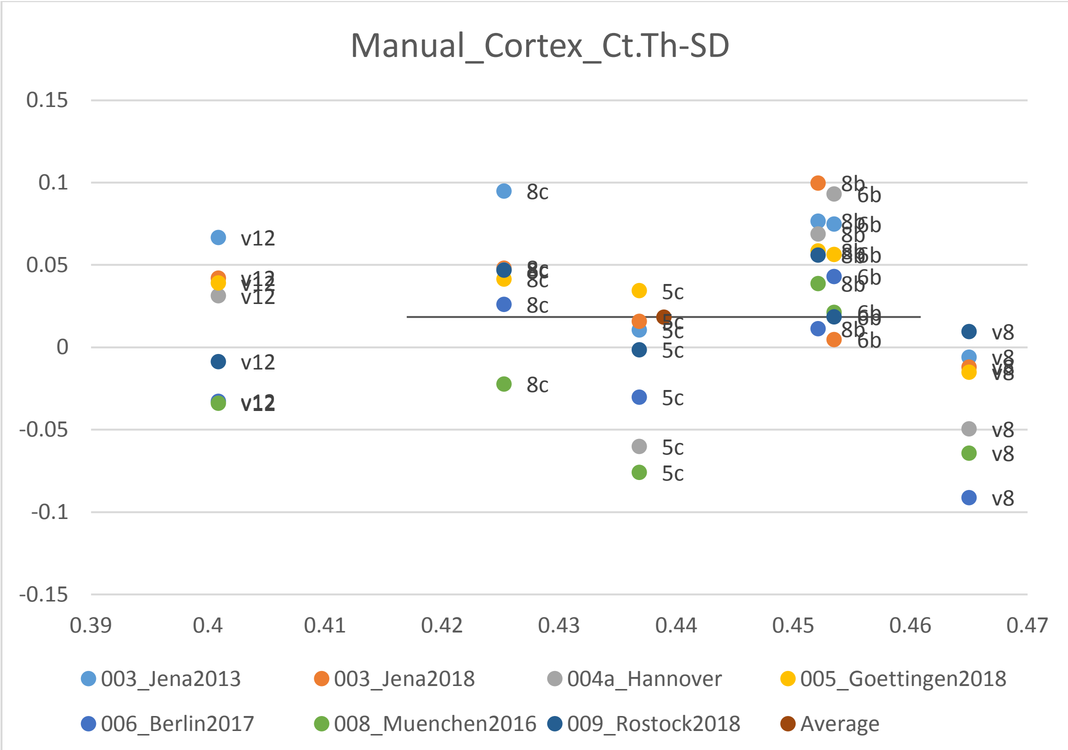
Difference Average/Method	Manual	Mask	Mesh
Ct.Th [mm]	0.129	-0.0084	0.1456
wCt.Th [mm]	0.0128	-0.0331	0.0097
Ct.Th-SD [mm]	0.0184	0.0025	0.0273
TV [cm^3]	0.3965	-0.054	0.3751
BMD [mg/cm^3]	-26.0123	-26.5438	-30.6118

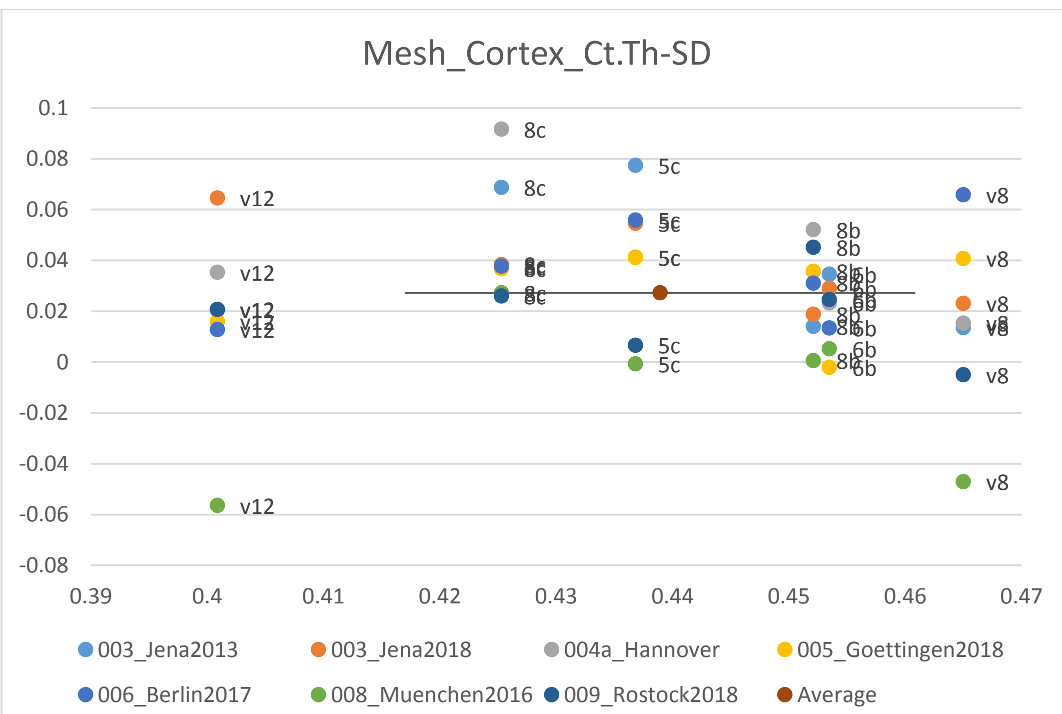

Manual_Cortex_Ct.Th
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
1.35
1.4
1.45
1.5
1.55
1.6
003_Jena2013
003_Jena2018
004a_Hannover
005_Goettingen2018
006_Berlin2017
008_Muenchen2016
009_Rostock2018
Average

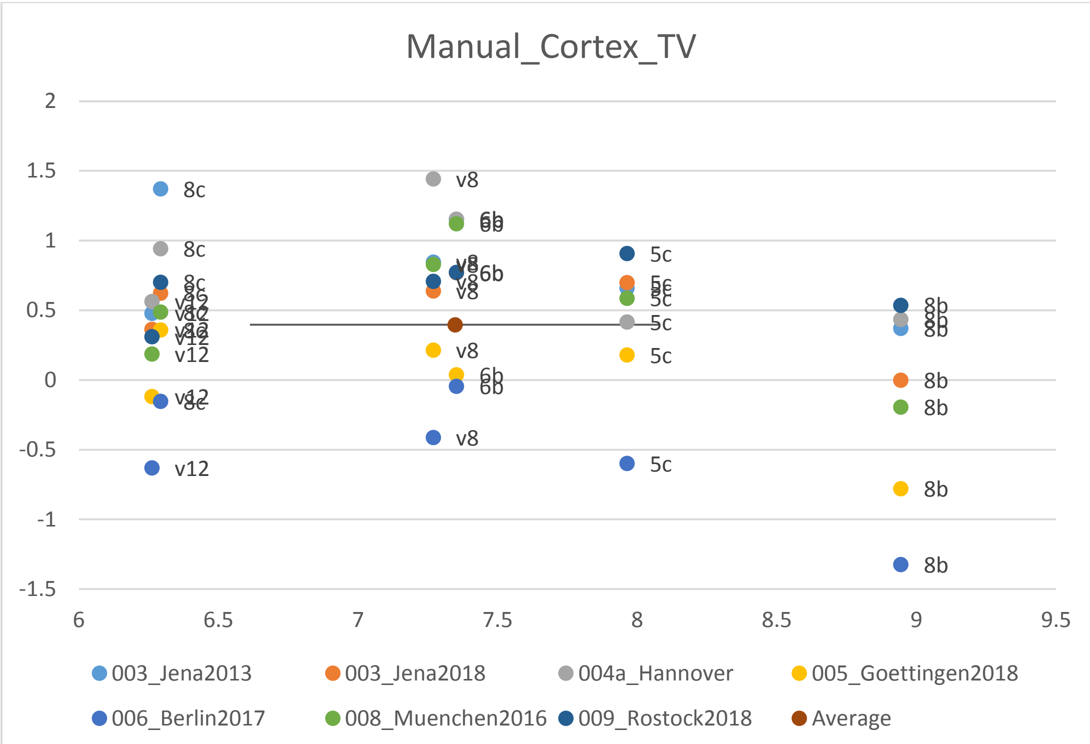

Mesh_Cortex_Ct.Th
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
1.35
1.4
1.45
1.5
1.55
1.6
003_Jena2013
003_Jena2018
004a_Hannover
005_Goettingen2018
006_Berlin2017
008_Muenchen2016
009_Rostock2018
Average

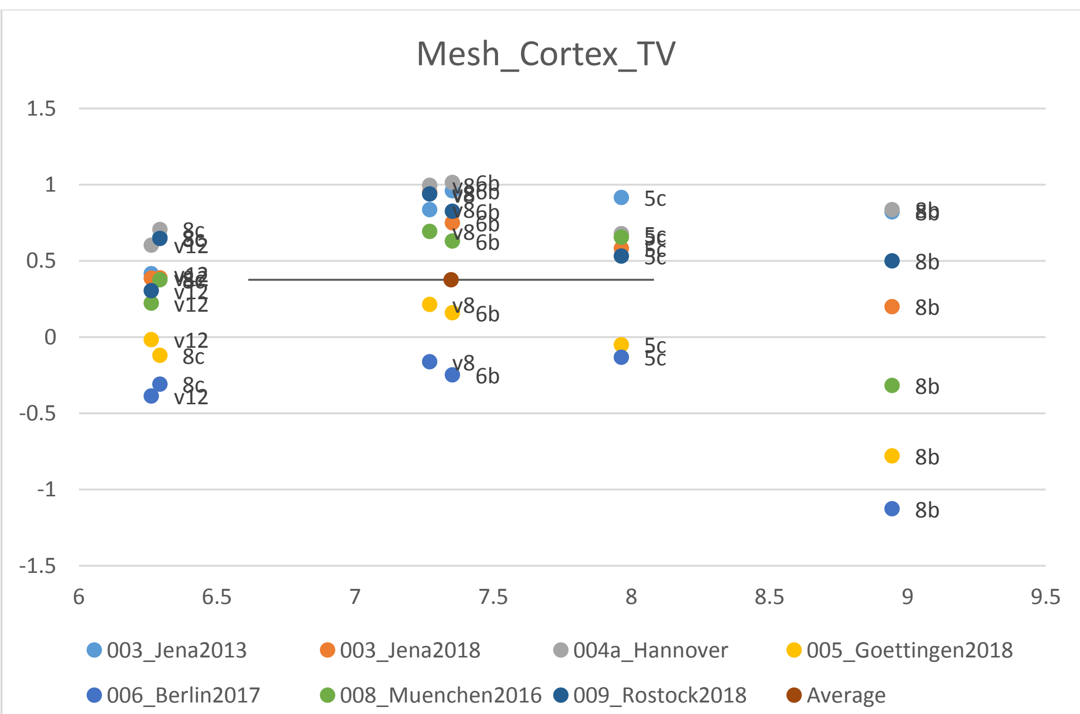

Manual_Cortex_wCt.Th
0.05
0.04
0.03
0.02
0.01
0
-0.01
-0.02
0.4
0.42
0.44
0.46
0.48
0.5
0.52
0.54
0.56
0.58
0.6
003_Jena2013
003_Jena2018
004a_Hannover
005_Goettingen2018
006_Berlin2017
008_Muenchen2016
009_Rostock2018
Average

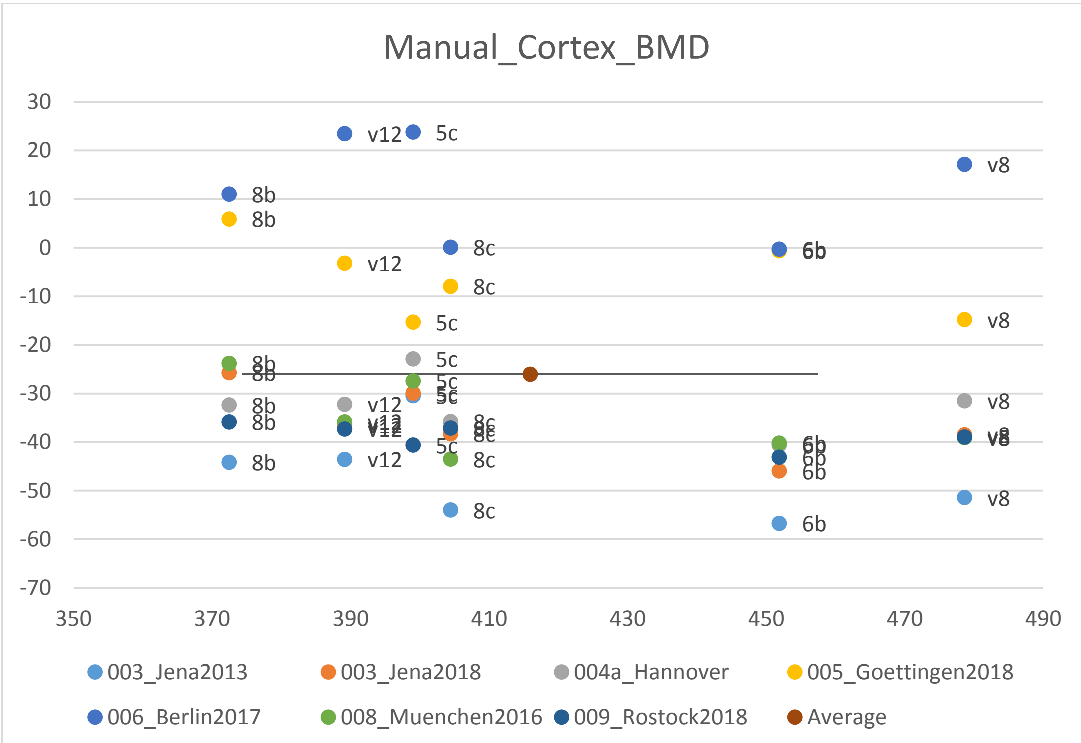

Mesh_Cortex_wCt.Th
0.05
0.04
0.03
0.02
0.01
0
-0.01
-0.02
-0.03
0.35
0.4
0.45
0.5
0.55
0.6
003_Jena2013
003_Jena2018
004a_Hannover
005_Goettingen2018
006_Berlin2017
008_Muenchen2016
009_Rostock2018
Average

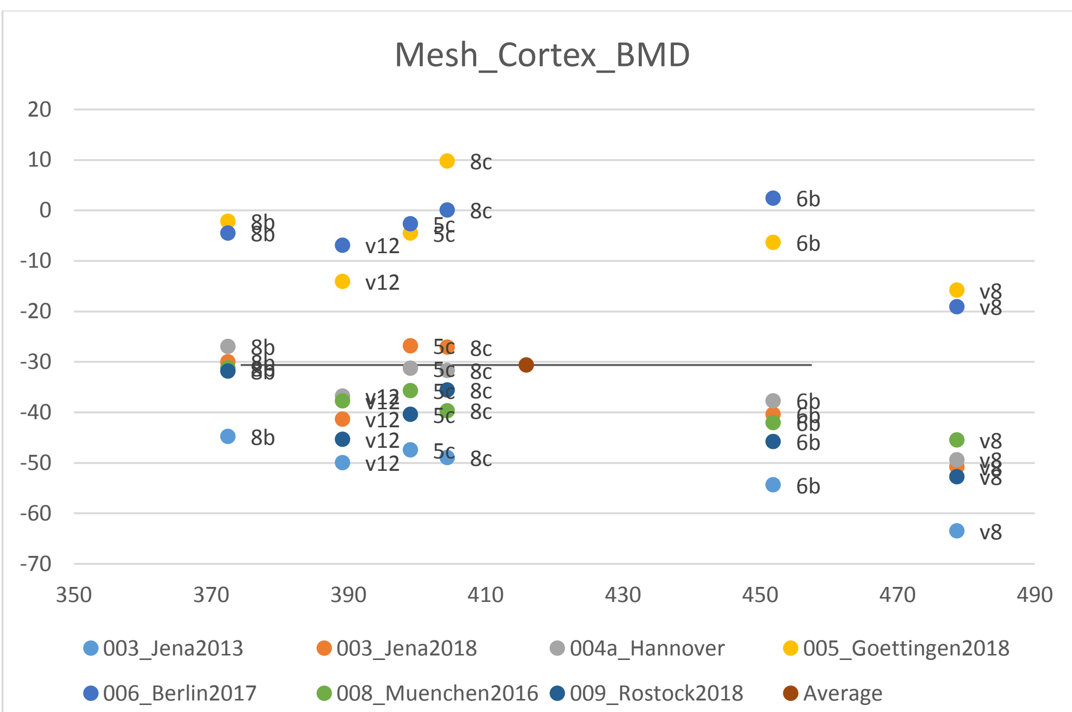

Manual_Cortex_Ct.Th-SD
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
0.39
0.4
0.41
0.42
0.43
0.44
0.45
0.46
0.47
v12
8c
5c
8b
6b
v8
003_Jena2013
003_Jena2018
004a_Hannover
005_Goettingen2018
006_Berlin2017
008_Muenchen2016
009_Rostock2018
Average


Mesh_Cortex_Ct.Th-SD
0.1
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
0.39
0.4
0.41
0.42
0.43
0.44
0.45
0.46
0.47
v12
8c
5c
8b
6b
v8
003_Jena2013
003_Jena2018
004a_Hannover
005_Goettingen2018
006_Berlin2017
008_Muenchen2016
009_Rostock2018
Average


Manual_Cortex_TV
2
1.5
1
0.5
0
-0.5
-1
-1.5
6
6.5
7
7.5
8
8.5
9
9.5
003_Jena2013
003_Jena2018
004a_Hannover
005_Goettingen2018
006_Berlin2017
008_Muenchen2016
009_Rostock2018
Average

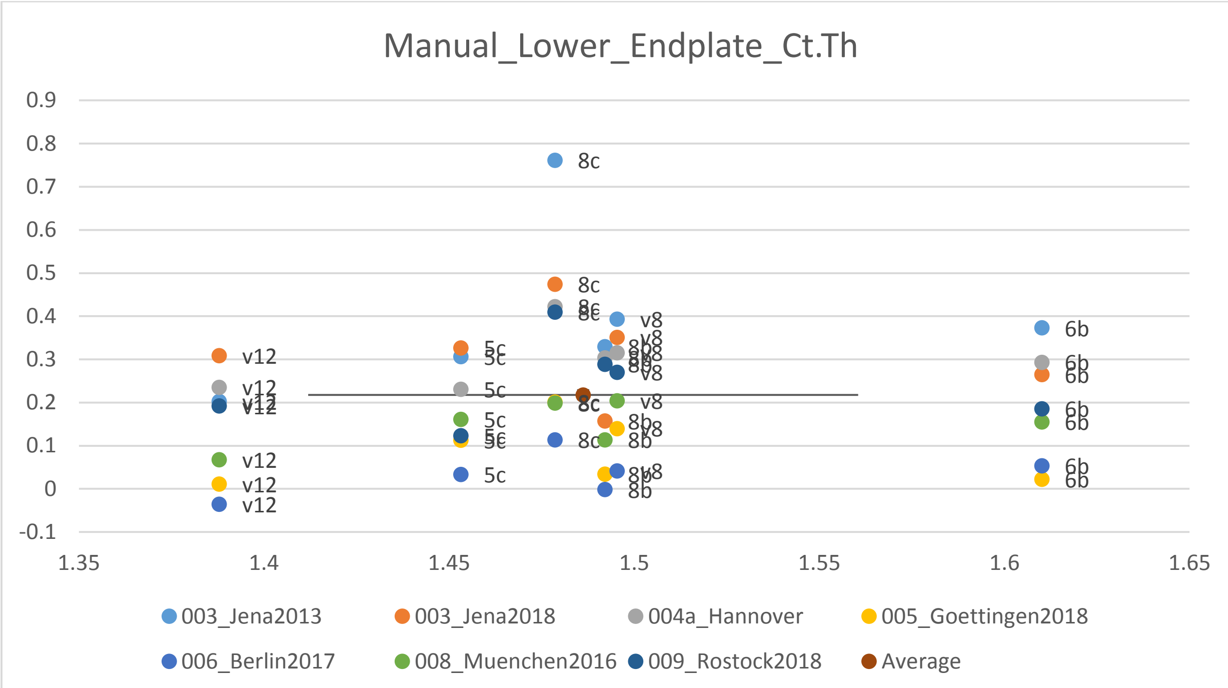

Mesh_Cortex_TV
1.5
1
0.5
0
-0.5
-1
-1.5
6
6.5
7
7.5
8
8.5
9
9.5
003_Jena2013
003_Jena2018
004a_Hannover
005_Goettingen2018
006_Berlin2017
008_Muenchen2016
009_Rostock2018
Average

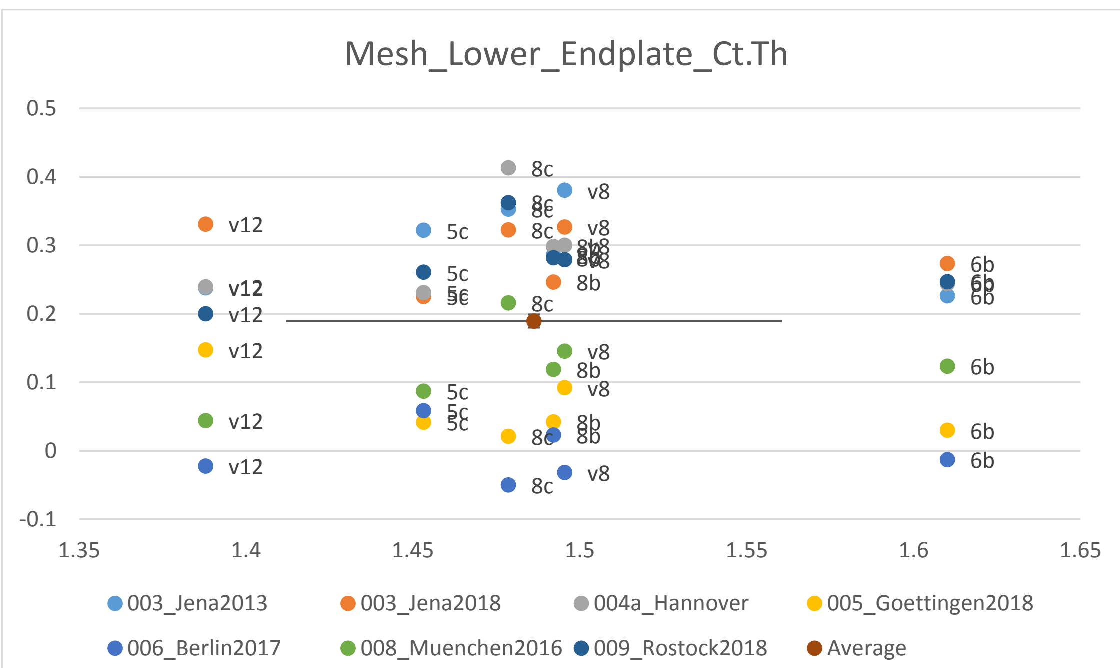

Manual_Cortex_BMD
30
20
10
0
-10
-20
-30
-40
-50
-60
-70
350
370
390
410
430
450
470
490
003_Jena2013
003_Jena2018
004a_Hannover
005_Goettingen2018
006_Berlin2017
008_Muenchen2016
009_Rostock2018
Average

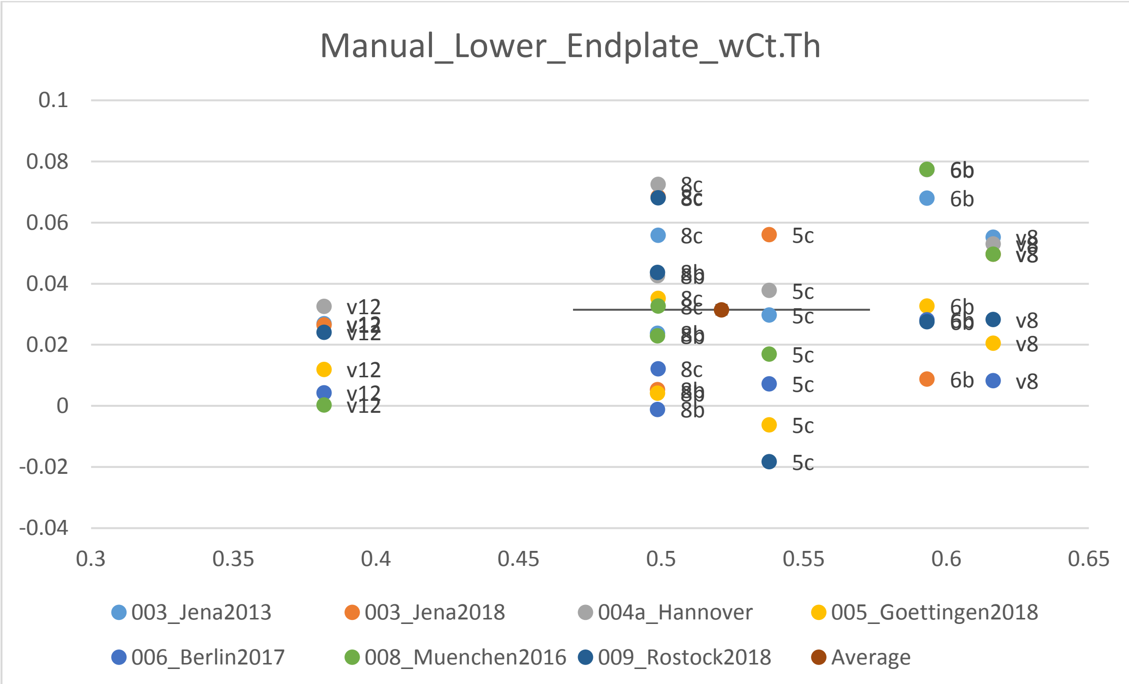

Mesh_Cortex_BMD
20
10
0
-10
-20
-30
-40
-50
-60
-70
350
370
390
410
430
450
470
490
003_Jena2013
003_Jena2018
004a_Hannover
005_Goettingen2018
006_Berlin2017
008_Muenchen2016
009_Rostock2018
Average

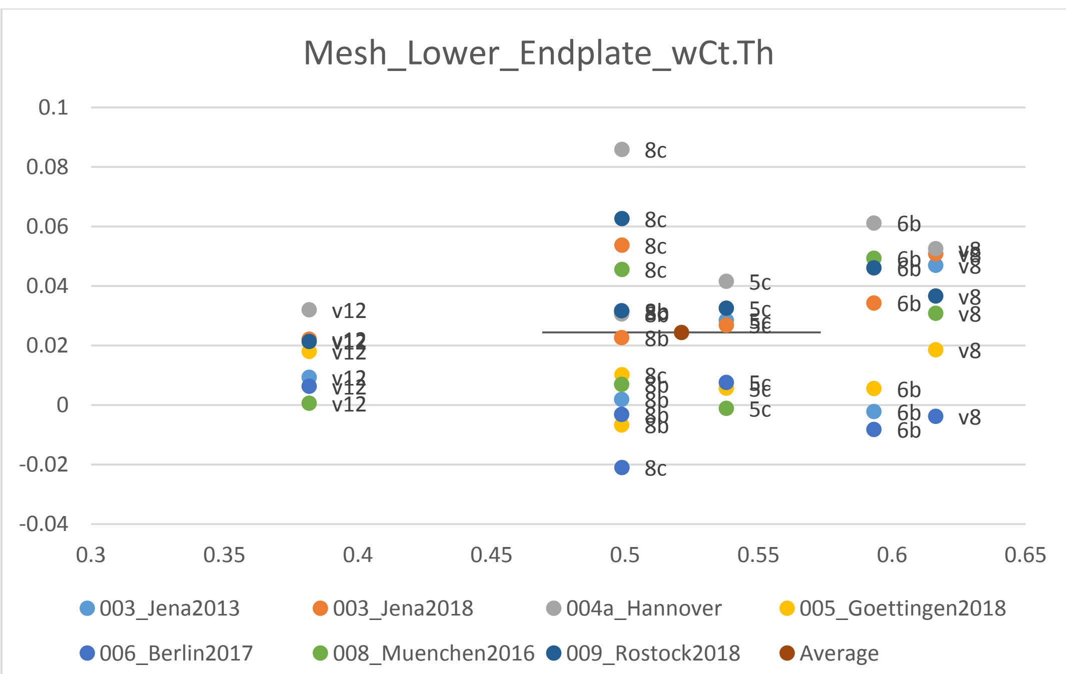
- **Lower_Endplate:**

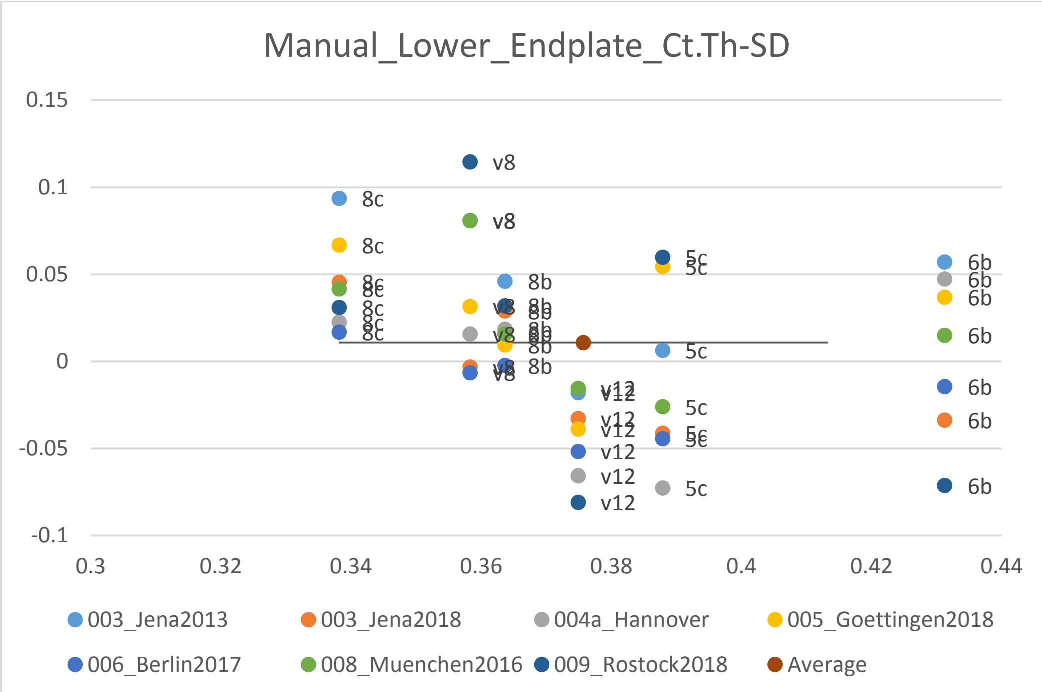
Difference Average/Method	Manual	Mask	Mesh
Ct.Th [mm]	0.2179	0.0092	0.1893
wCt.Th [mm]	0.0314	-0.0278	0.0243
Ct.Th-SD [mm]	0.0107	0.0021	-0.007
TV [cm^3]	0.3187	0.0181	0.315
BMD [mg/cm^3]	-31.1778	-23.7607	-29.7543

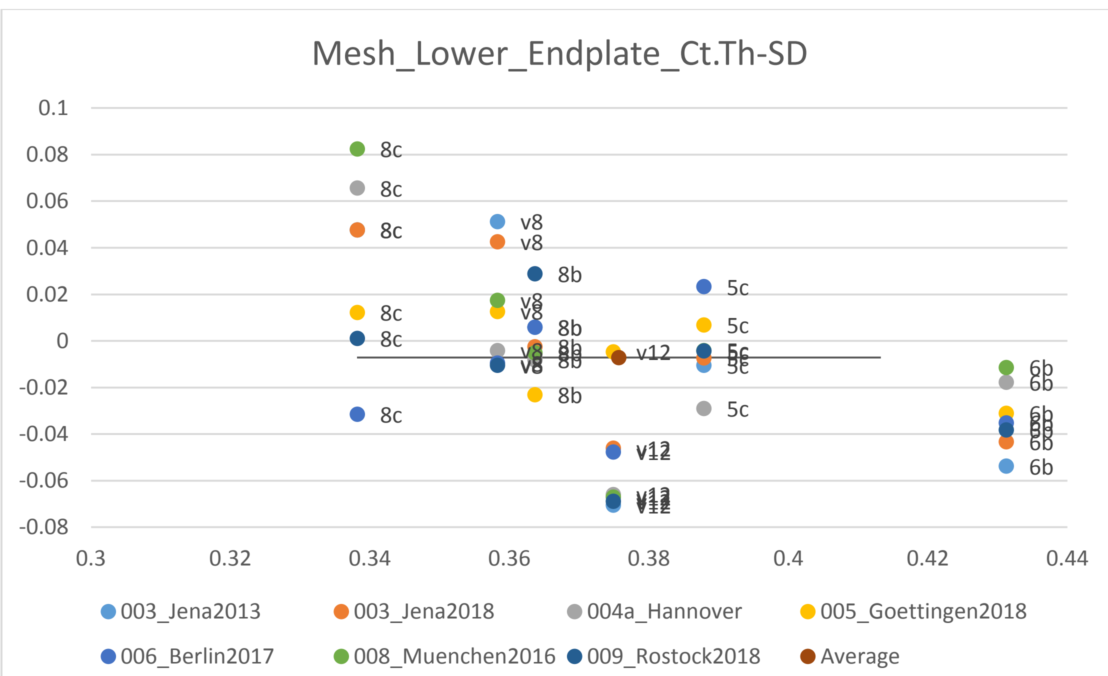

Manual_Lower_Endplate_Ct.Th
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
1.35
1.4
1.45
1.5
1.55
1.6
1.65
003_Jena2013
003_Jena2018
004a_Hannover
005_Goettingen2018
006_Berlin2017
008_Muenchen2016
009_Rostock2018
Average

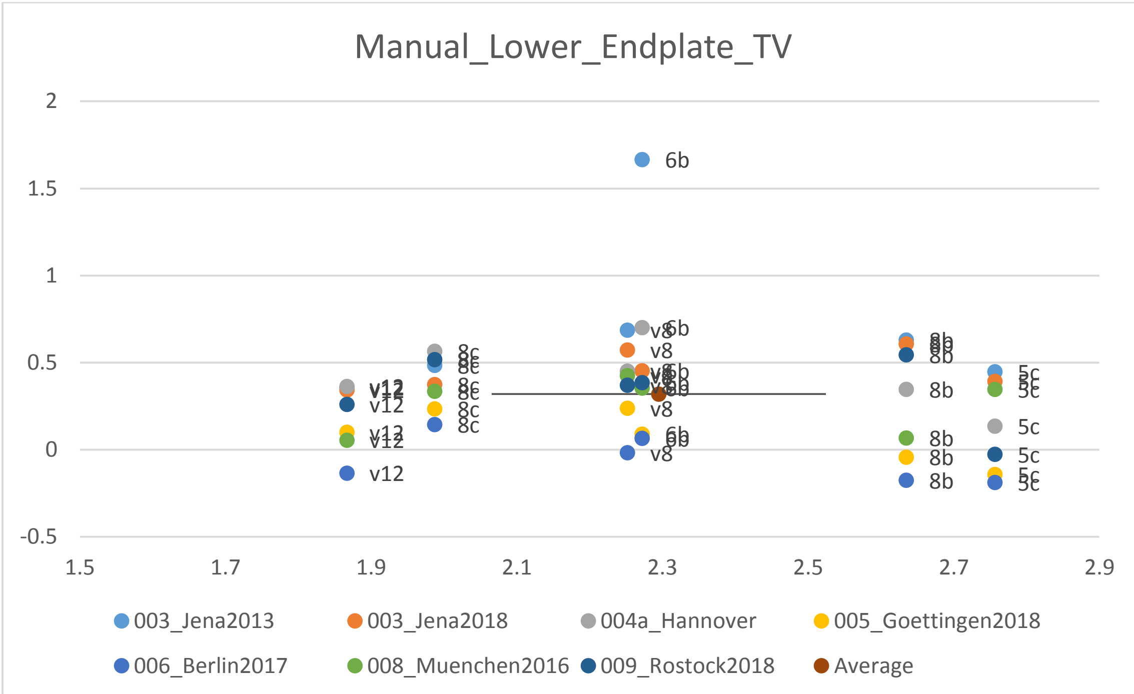

Mesh_Lower_Endplate_Ct.Th
0.5
0.4
0.3
0.2
0.1
0
-0.1
1.35
1.4
1.45
1.5
1.55
1.6
1.65
003_Jena2013
003_Jena2018
004a_Hannover
005_Goettingen2018
006_Berlin2017
008_Muenchen2016
009_Rostock2018
Average

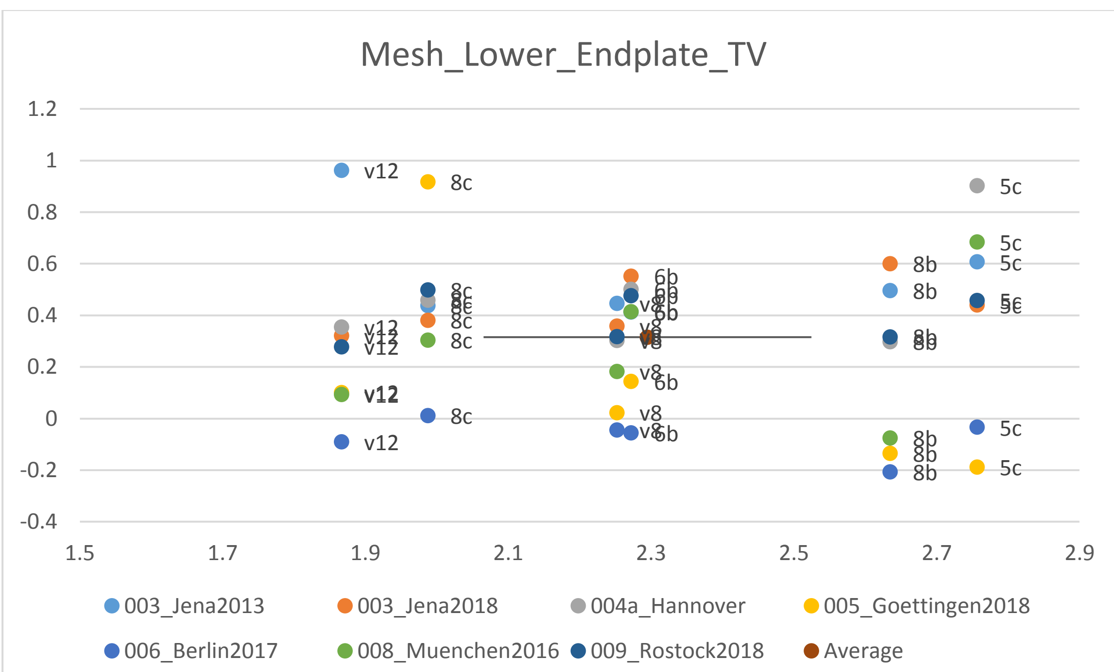

Manual_Lower_Endplate_wCt.Th
0.1
0.08
0.06
0.04
0.02
0
-0.02
-0.04
0.3
0.35
0.4
0.45
0.5
0.55
0.6
0.65
v12
8c
8b
5c
6b
v8
003_Jena2013
003_Jena2018
004a_Hannover
005_Goettingen2018
006_Berlin2017
008_Muenchen2016
009_Rostock2018
Average

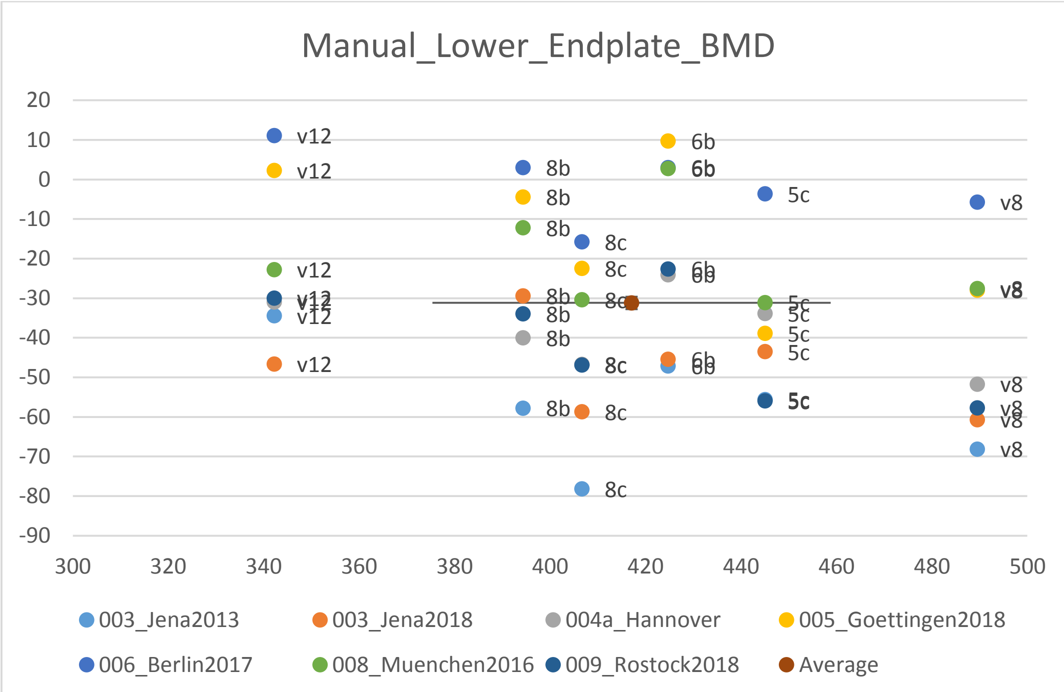

Mesh_Lower_Endplate_wCt.Th
0.1
0.08
0.06
0.04
0.02
0
-0.02
-0.04
0.3
0.35
0.4
0.45
0.5
0.55
0.6
0.65
v12
8c
8b
5c
6b
v8
003_Jena2013
003_Jena2018
004a_Hannover
005_Goettingen2018
006_Berlin2017
008_Muenchen2016
009_Rostock2018
Average

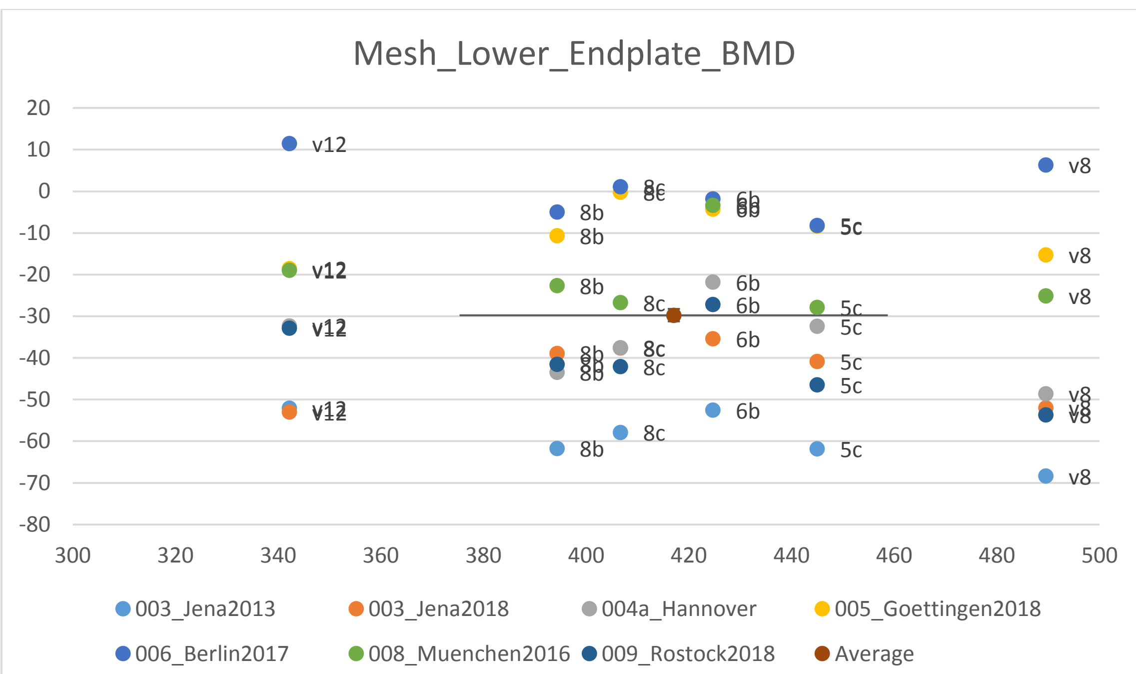

Manual_Lower_Endplate_Ct.Th-SD
0.15
0.1
0.05
0
-0.05
-0.1
0.3
0.32
0.34
0.36
0.38
0.4
0.42
0.44
003_Jena2013
003_Jena2018
004a_Hannover
005_Goettingen2018
006_Berlin2017
008_Muenchen2016
009_Rostock2018
Average


Mesh_Lower_Endplate_Ct.Th-SD
0.1
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
0.3
0.32
0.34
0.36
0.38
0.4
0.42
0.44
003_Jena2013
003_Jena2018
004a_Hannover
005_Goettingen2018
006_Berlin2017
008_Muenchen2016
009_Rostock2018
Average


Manual_Lower_Endplate_TV
2
1.5
1
0.5
0
-0.5
1.5
1.7
1.9
2.1
2.3
2.5
2.7
2.9
003_Jena2013
003_Jena2018
004a_Hannover
005_Goettingen2018
006_Berlin2017
008_Muenchen2016
009_Rostock2018
Average

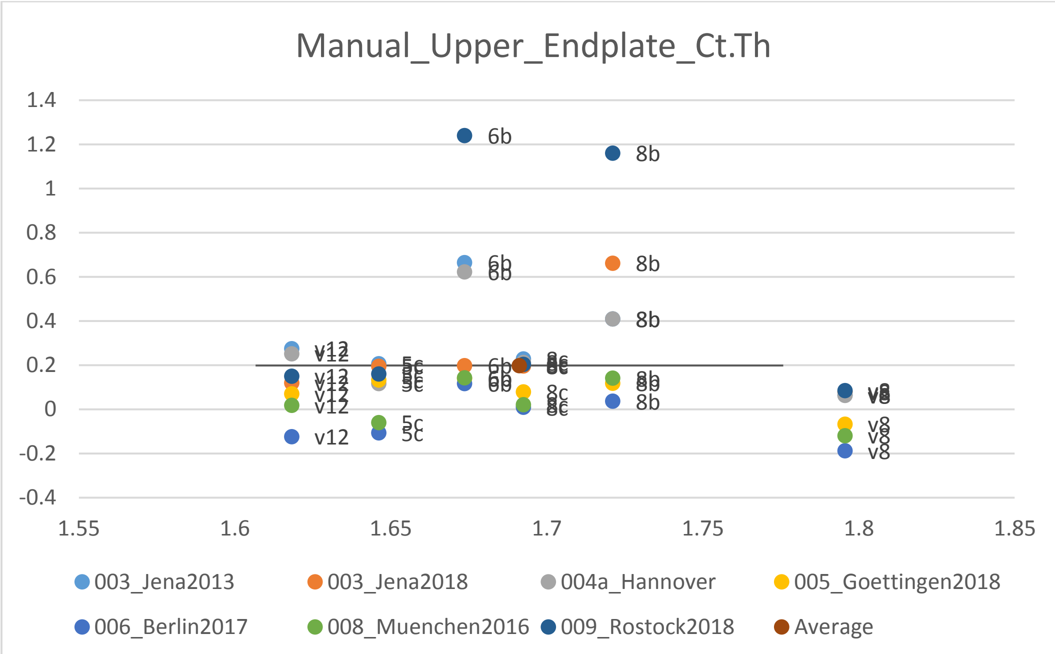

Mesh_Lower_Endplate_TV
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
1.5
1.7
1.9
2.1
2.3
2.5
2.7
2.9
003_Jena2013
003_Jena2018
004a_Hannover
005_Goettingen2018
006_Berlin2017
008_Muenchen2016
009_Rostock2018
Average

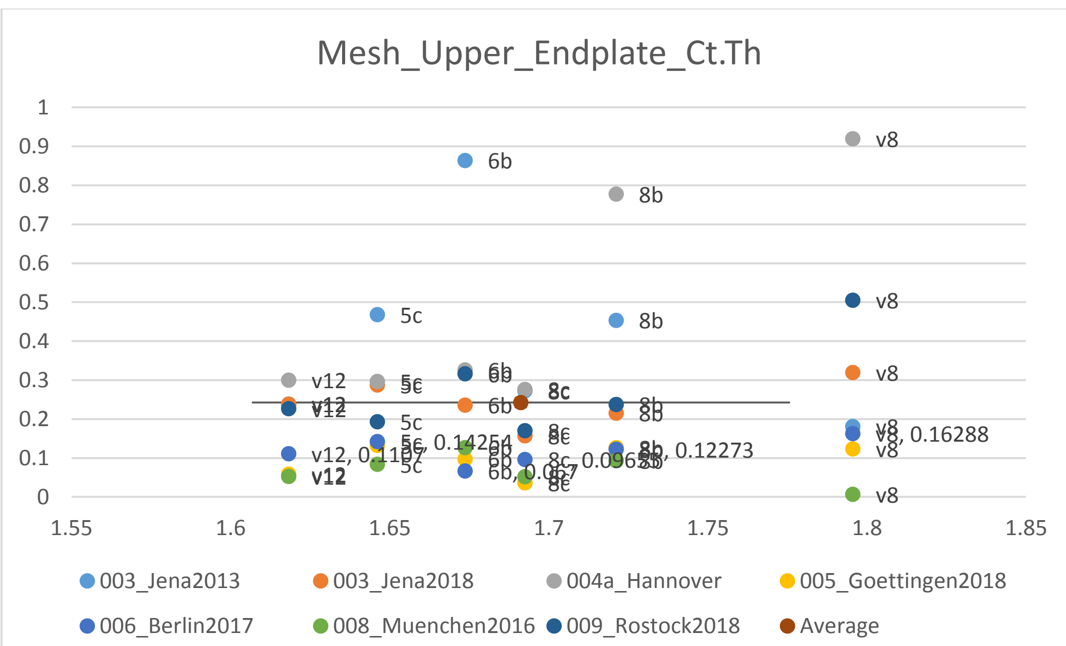

Manual_Lower_Endplate_BMD
20
10
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
300
320
340
360
380
400
420
440
460
480
500
v12
8b
8c
6b
5c
v8
003_Jena2013
003_Jena2018
004a_Hannover
005_Goettingen2018
006_Berlin2017
008_Muenchen2016
009_Rostock2018
Average

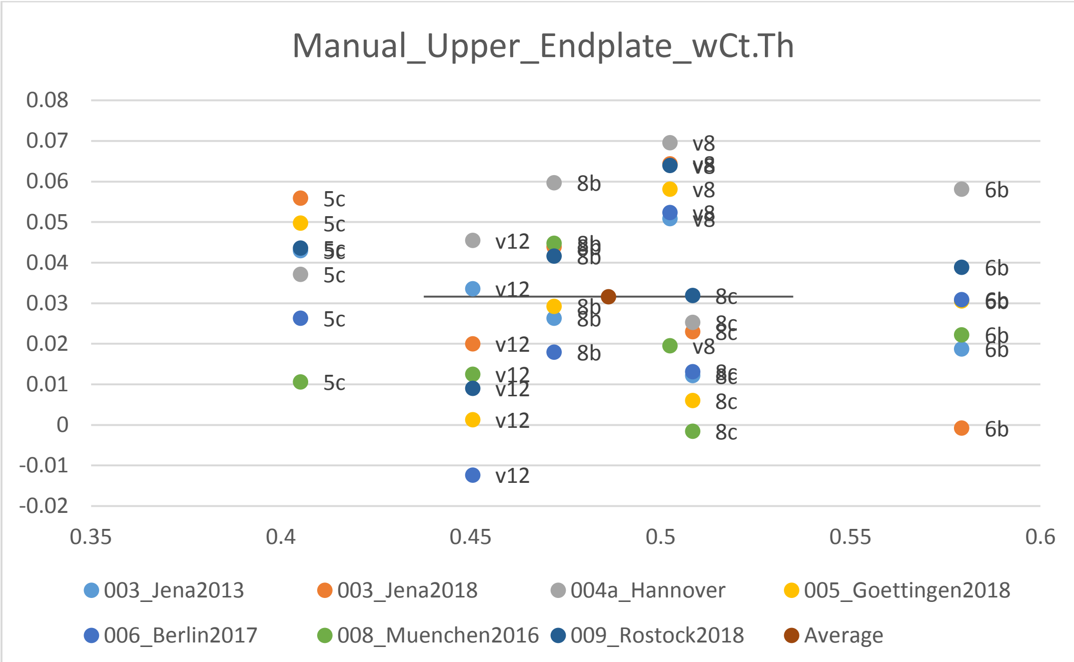

Mesh_Lower_Endplate_BMD
20
10
0
-10
-20
-30
-40
-50
-60
-70
-80
300
320
340
360
380
400
420
440
460
480
500
v12
8b
8c
6b
5c
v8
003_Jena2013
003_Jena2018
004a_Hannover
005_Goettingen2018
006_Berlin2017
008_Muenchen2016
009_Rostock2018
Average

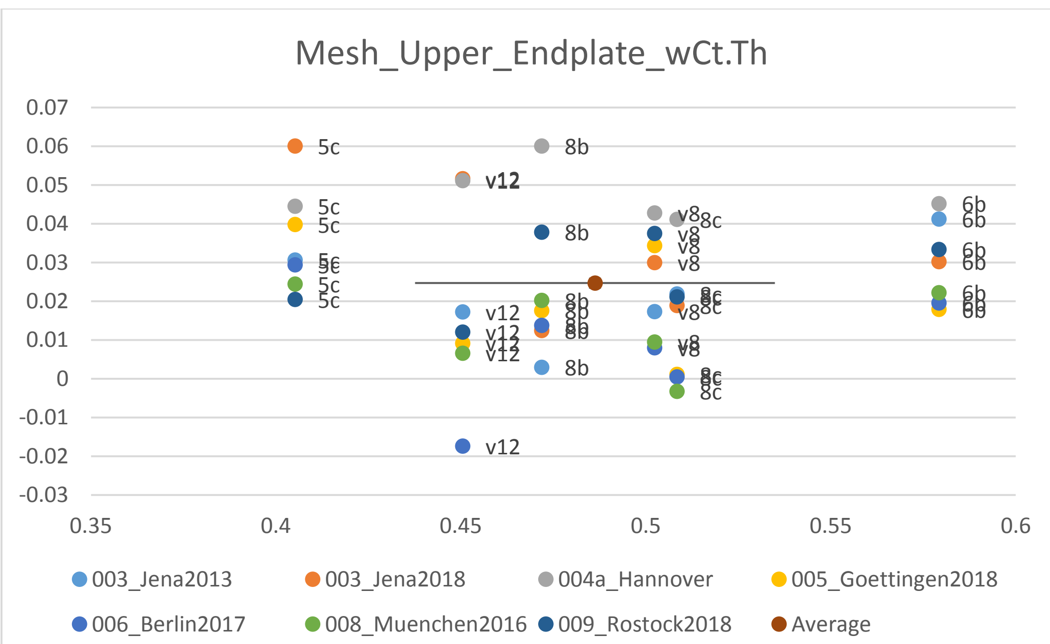
- **Upper_Endplate:**

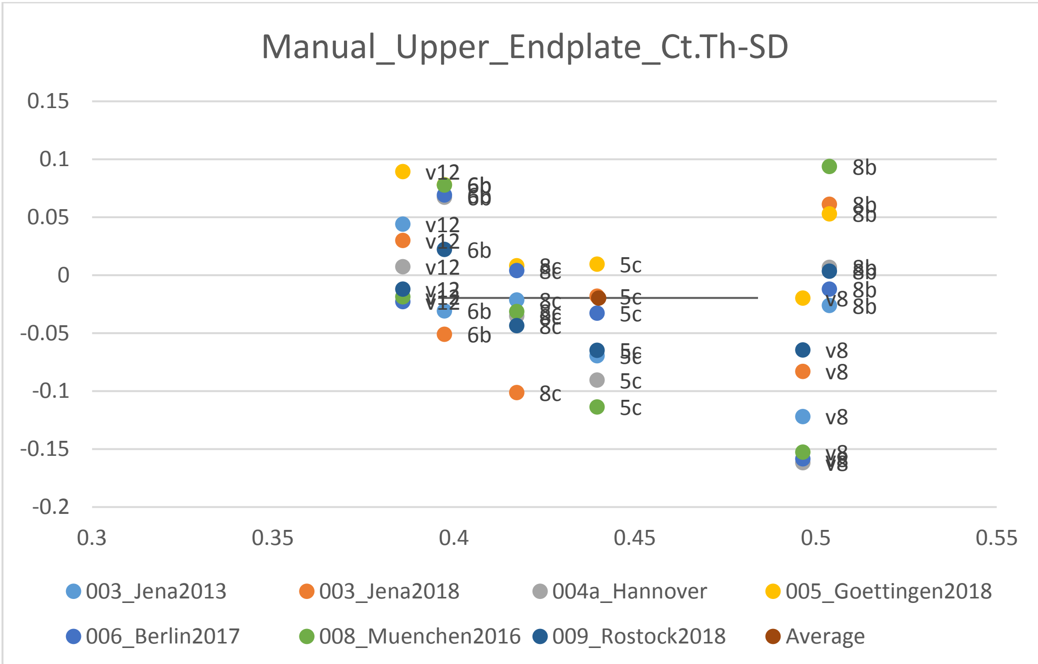
Difference Average/Method	Manual	Mask	Mesh
Ct.Th [mm]	0.1992	-0.0065	0.2421
wCt.Th [mm]	0.0316	-0.0281	0.0246
Ct.Th-SD [mm]	-0.0196	-0.0013	0.0038
TV [cm^3]	0.3629	-0.0054	0.3565
BMD [mg/cm^3]	-8.4258	-18.9271	-20.9961

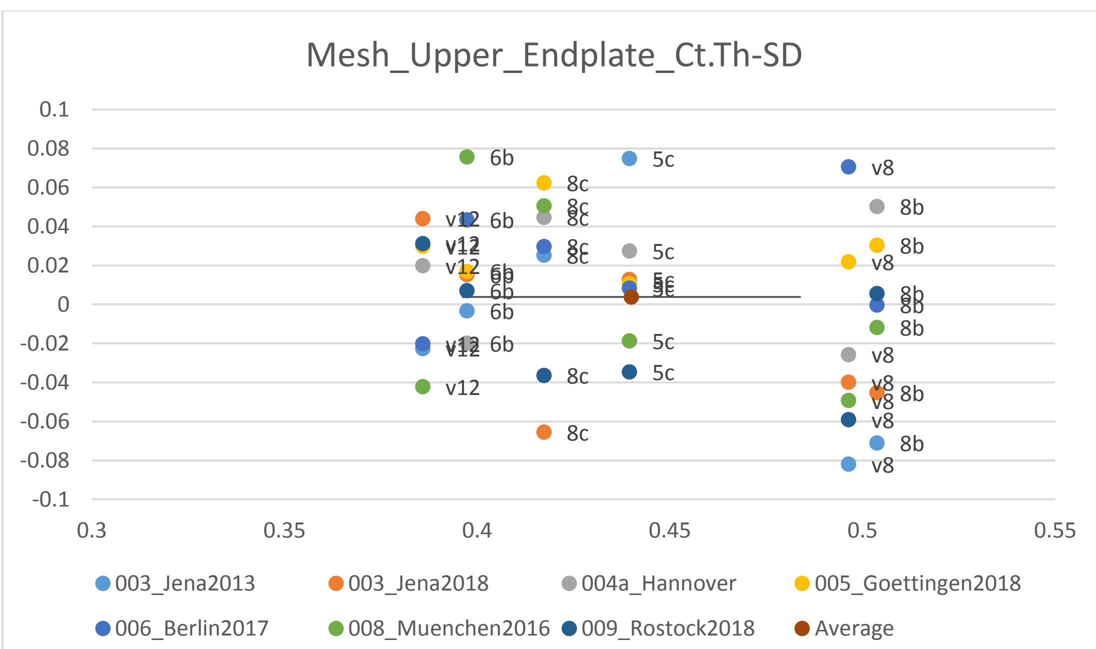

Manual_Upper_Endplate_Ct.Th
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
1.55
1.6
1.65
1.7
1.75
1.8
1.85
6b
8b
v12
5c
8c
v8
003_Jena2013
003_Jena2018
004a_Hannover
005_Goettingen2018
006_Berlin2017
008_Muenchen2016
009_Rostock2018
Average

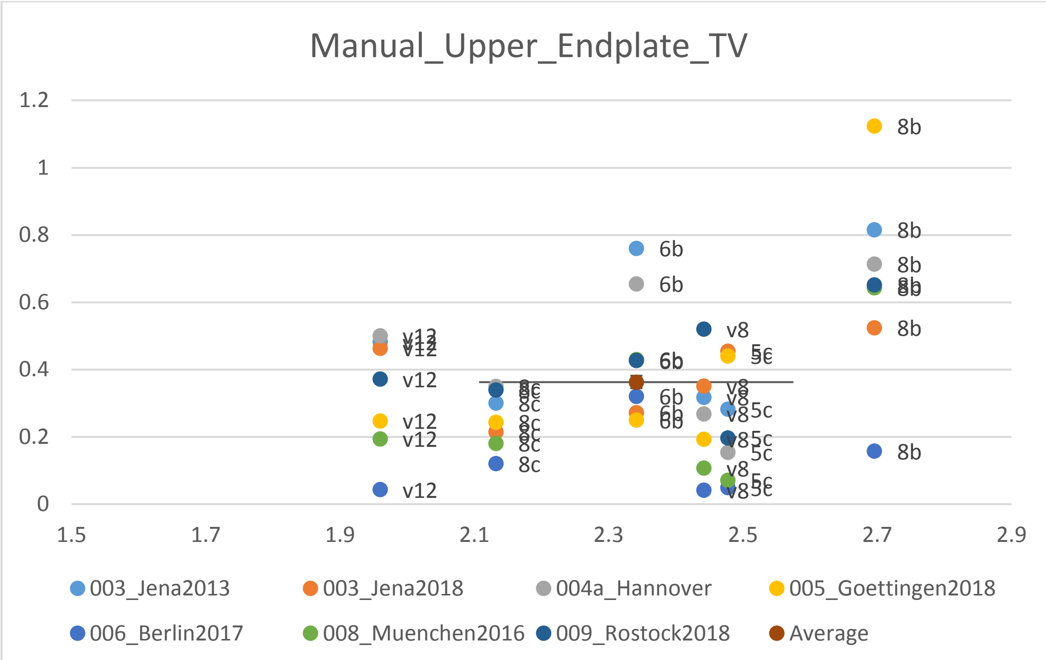

Mesh_Upper_Endplate_Ct.Th
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1.55
1.6
1.65
1.7
1.75
1.8
1.85
6b
8b
v8
5c
v12
8c
v8, 0.16288
8b, 0.12273
003_Jena2013
003_Jena2018
004a_Hannover
005_Goettingen2018
006_Berlin2017
008_Muenchen2016
009_Rostock2018
Average

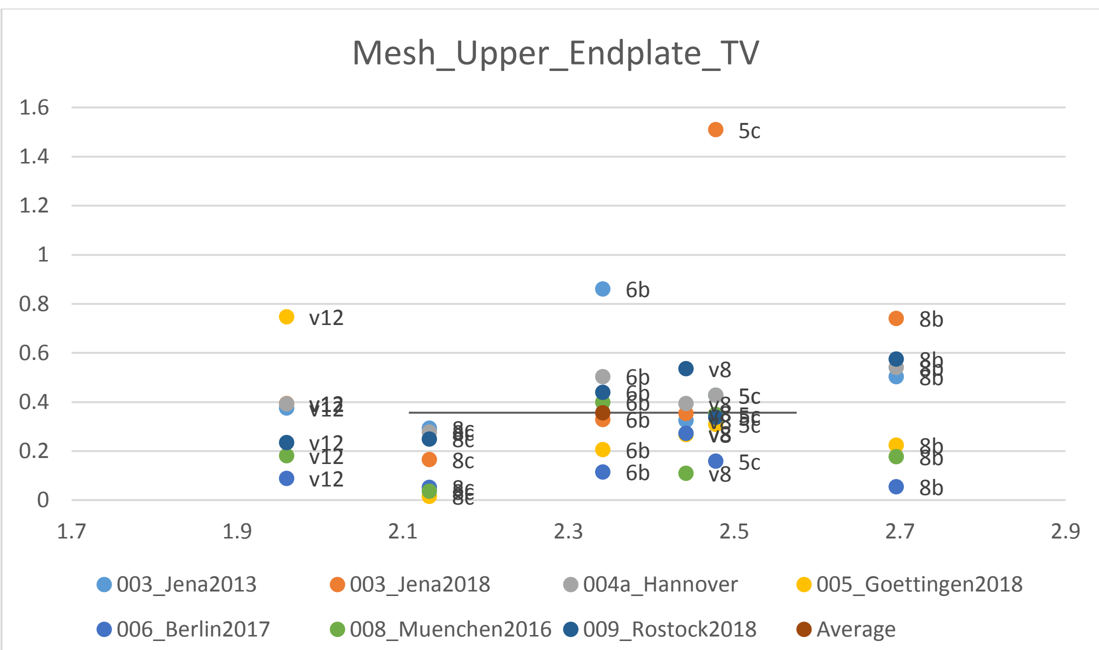

Manual_Upper_Endplate_wCt.Th
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
-0.01
-0.02
0.35
0.4
0.45
0.5
0.55
0.6
003_Jena2013
003_Jena2018
004a_Hannover
005_Goettingen2018
006_Berlin2017
008_Muenchen2016
009_Rostock2018
Average

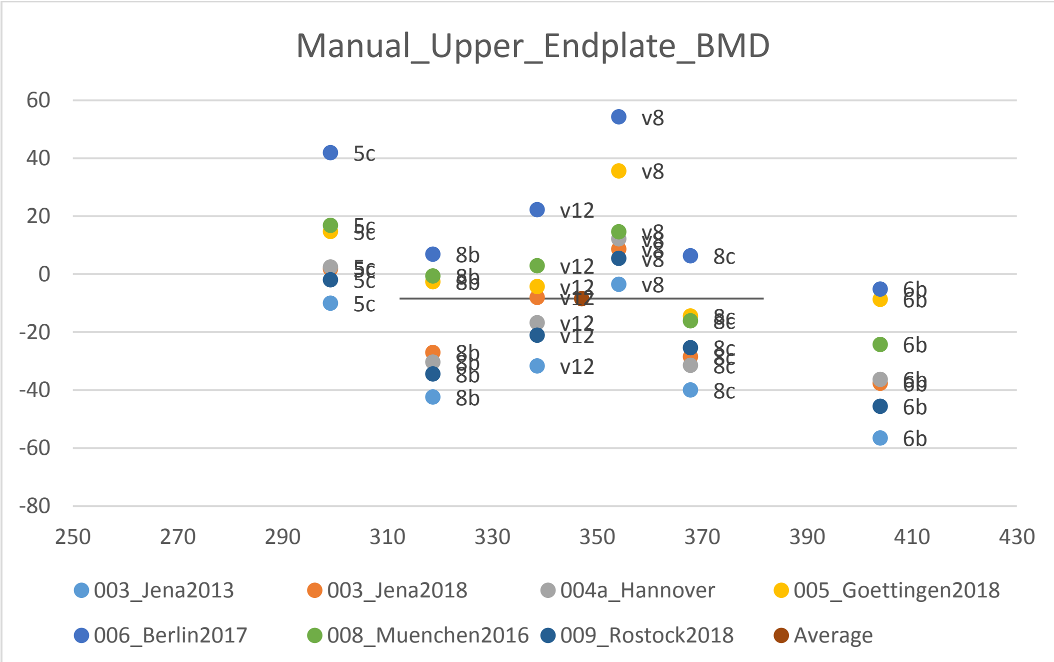

Mesh_Upper_Endplate_wCt.Th
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
-0.01
-0.02
-0.03
0.35
0.4
0.45
0.5
0.55
0.6
003_Jena2013
003_Jena2018
004a_Hannover
005_Goettingen2018
006_Berlin2017
008_Muenchen2016
009_Rostock2018
Average

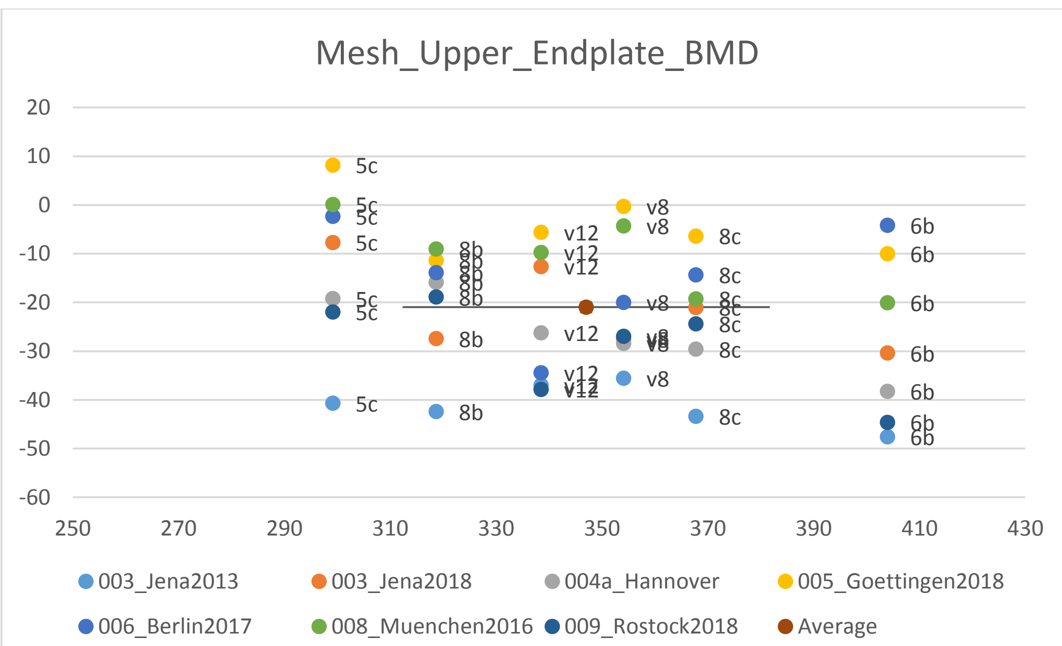

Manual_Upper_Endplate_Ct.Th-SD
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
0.3
0.35
0.4
0.45
0.5
0.55
003_Jena2013
003_Jena2018
004a_Hannover
005_Goettingen2018
006_Berlin2017
008_Muenchen2016
009_Rostock2018
Average


Mesh_Upper_Endplate_Ct.Th-SD
0.1
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
-0.1
0.3
0.35
0.4
0.45
0.5
0.55
003_Jena2013
003_Jena2018
004a_Hannover
005_Goettingen2018
006_Berlin2017
008_Muenchen2016
009_Rostock2018
Average

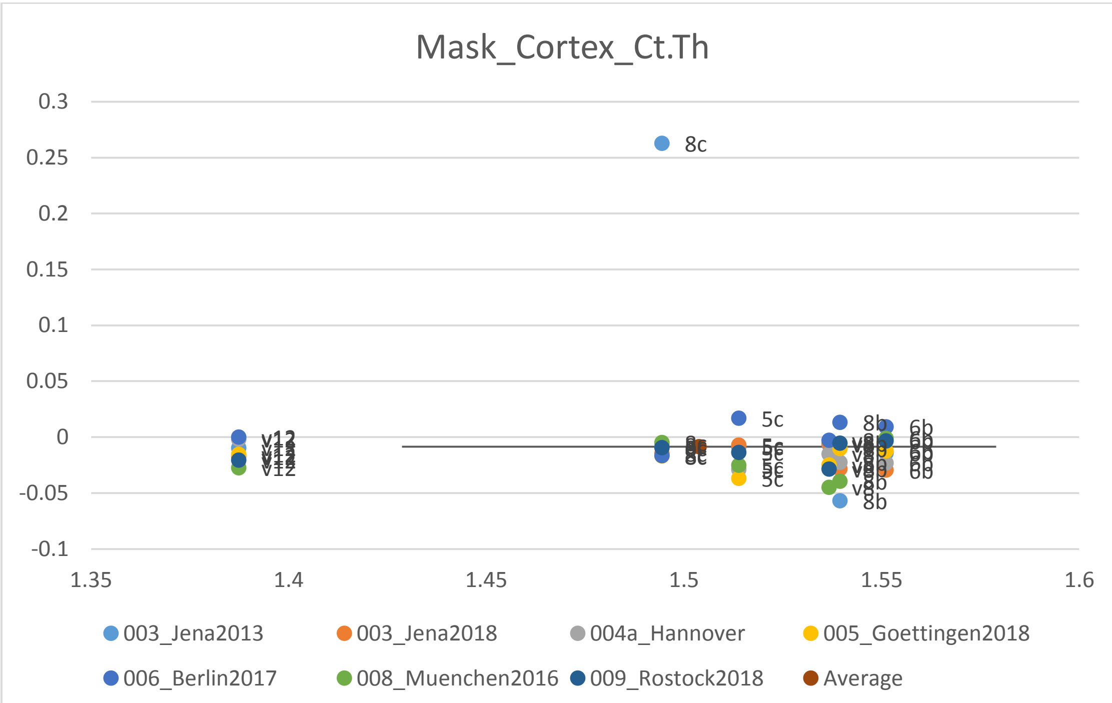

Manual_Upper_Endplate_TV
1.2
1
0.8
0.6
0.4
0.2
0
1.5
1.7
1.9
2.1
2.3
2.5
2.7
2.9
003_Jena2013
003_Jena2018
004a_Hannover
005_Goettingen2018
006_Berlin2017
008_Muenchen2016
009_Rostock2018
Average

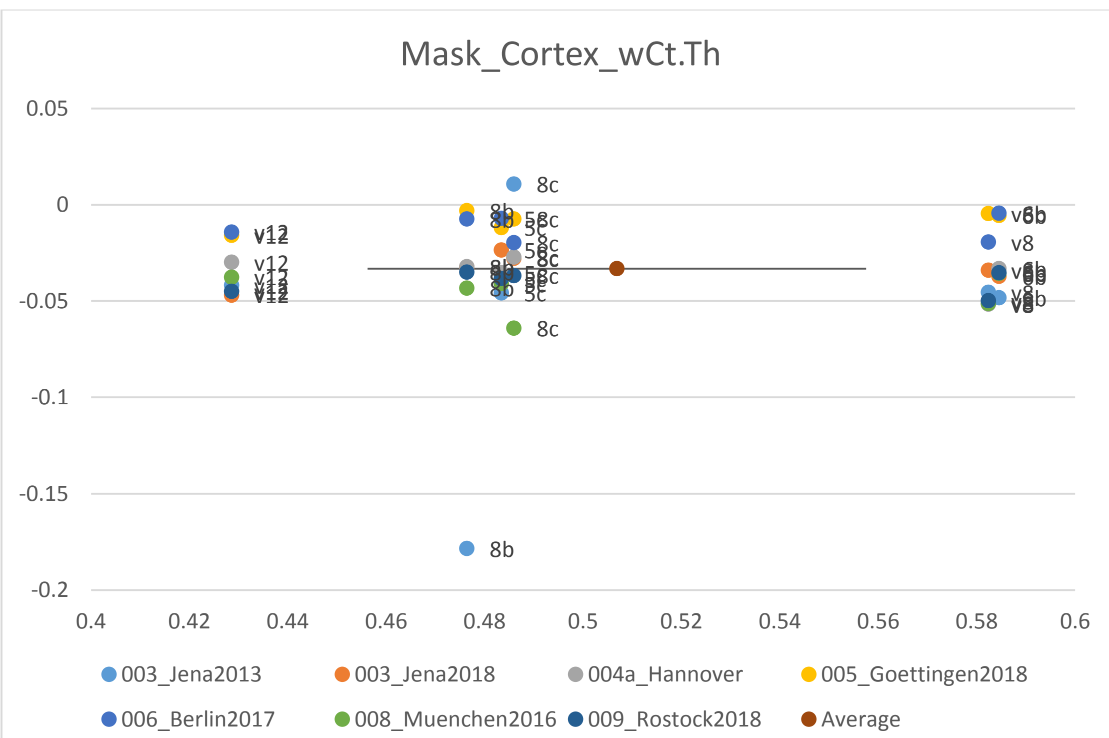

Mesh_Upper_Endplate_TV
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1.7
1.9
2.1
2.3
2.5
2.7
2.9
003_Jena2013
003_Jena2018
004a_Hannover
005_Goettingen2018
006_Berlin2017
008_Muenchen2016
009_Rostock2018
Average

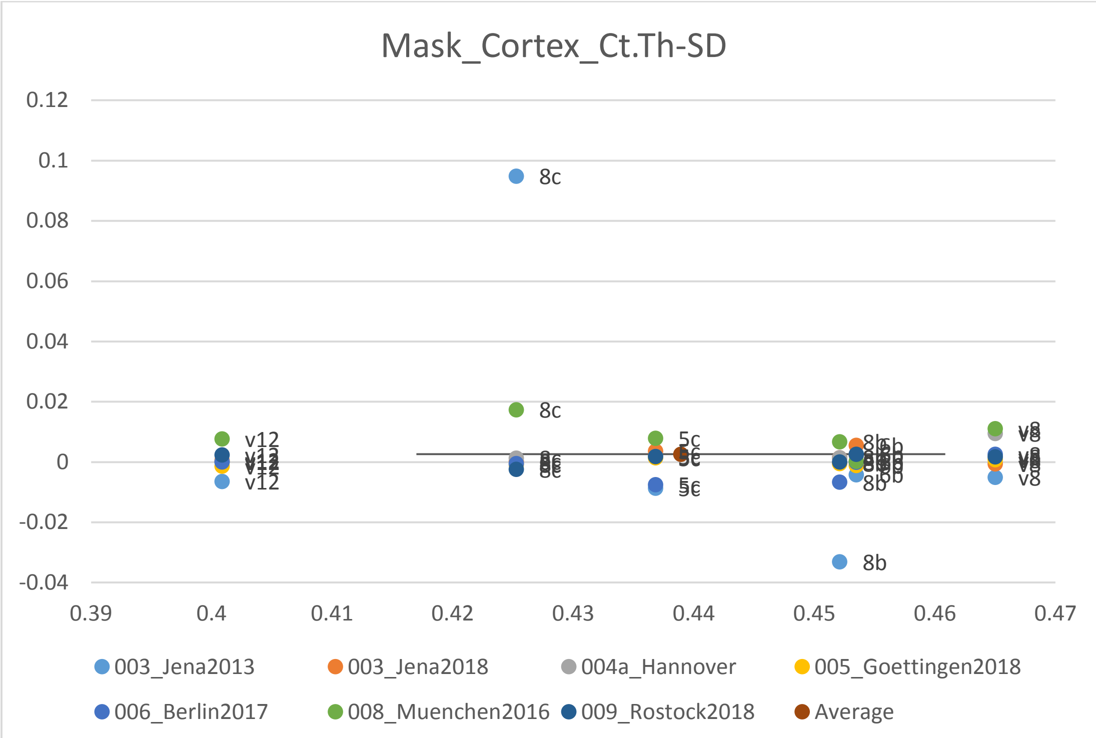

Manual_Upper_Endplate_BMD
60
40
20
0
-20
-40
-60
-80
250
270
290
310
330
350
370
390
410
430
003_Jena2013
003_Jena2018
004a_Hannover
005_Goettingen2018
006_Berlin2017
008_Muenchen2016
009_Rostock2018
Average

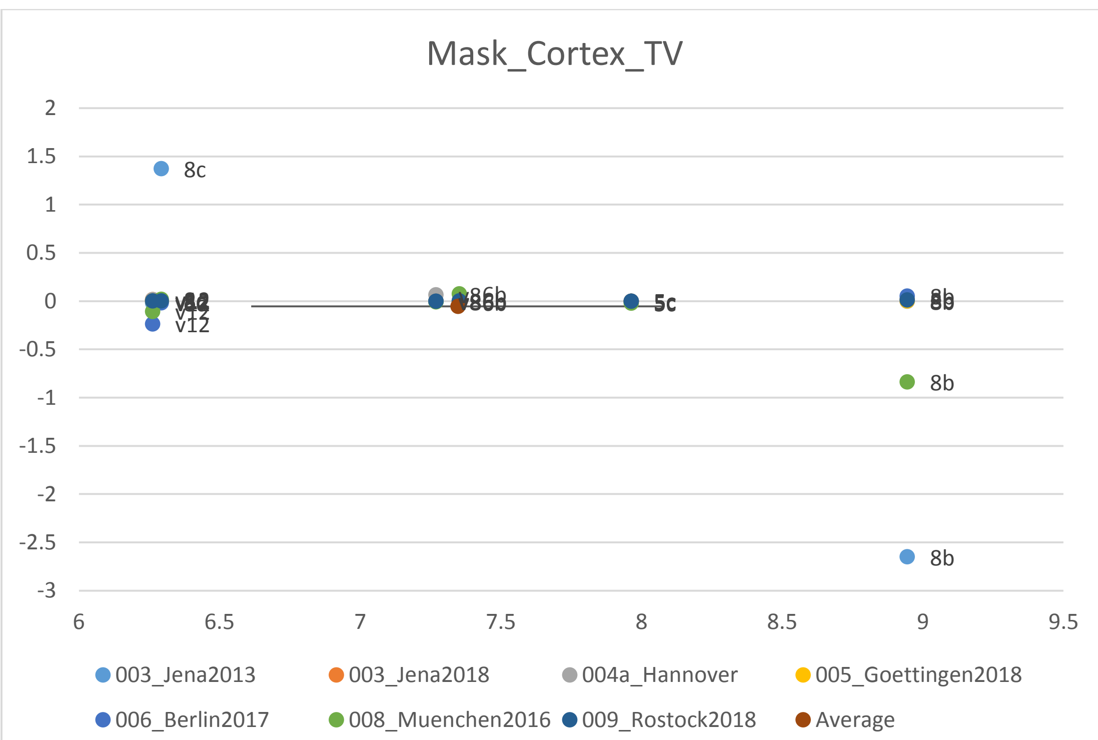

Mesh_Upper_Endplate_BMD
20
10
0
-10
-20
-30
-40
-50
-60
250
270
290
310
330
350
370
390
410
430
003_Jena2013
003_Jena2018
004a_Hannover
005_Goettingen2018
006_Berlin2017
008_Muenchen2016
009_Rostock2018
Average

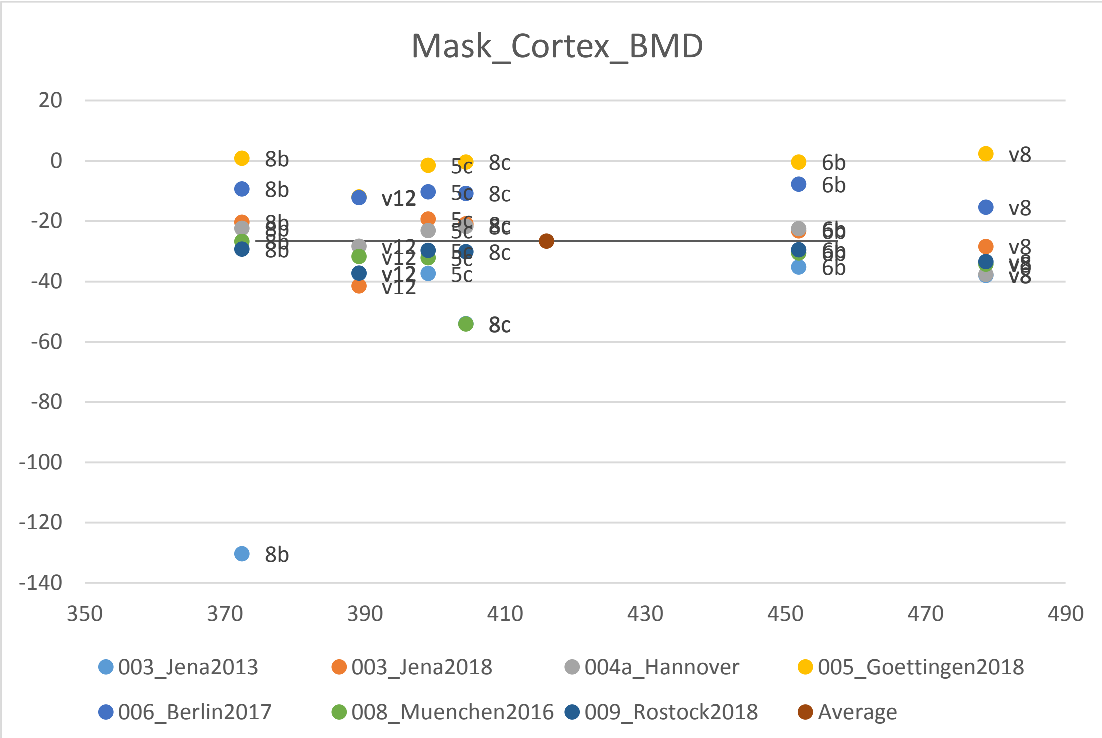
- **Bland-Altman for Mask:**
  - **Cortex:**



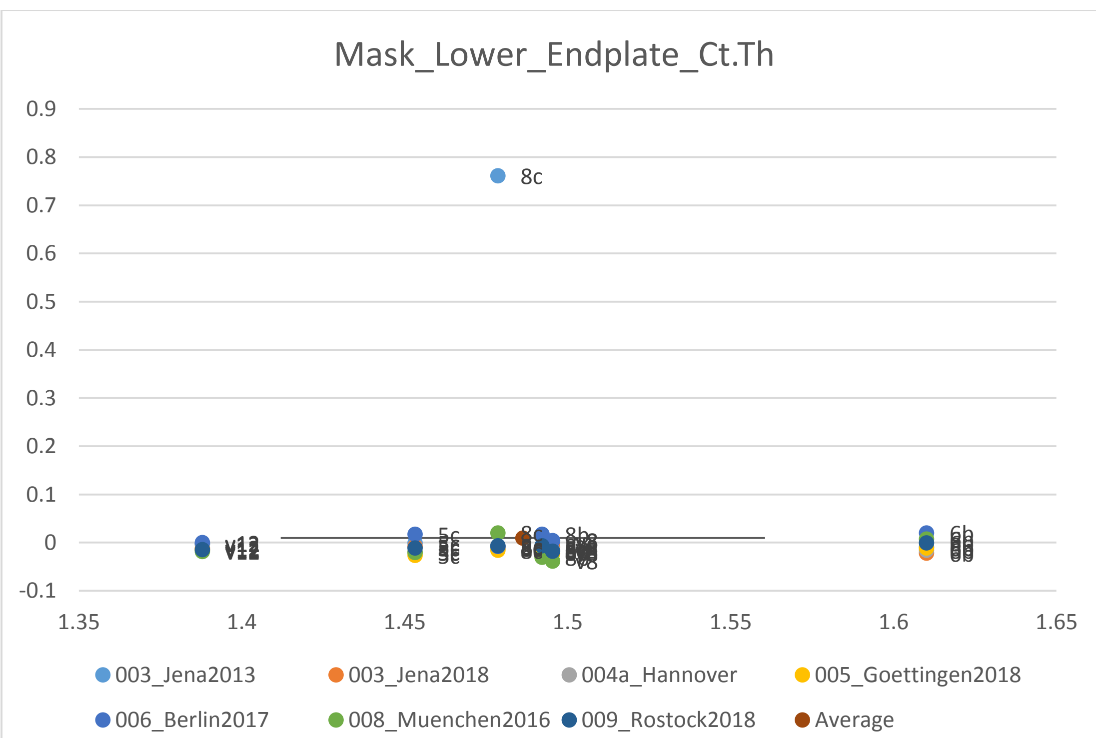


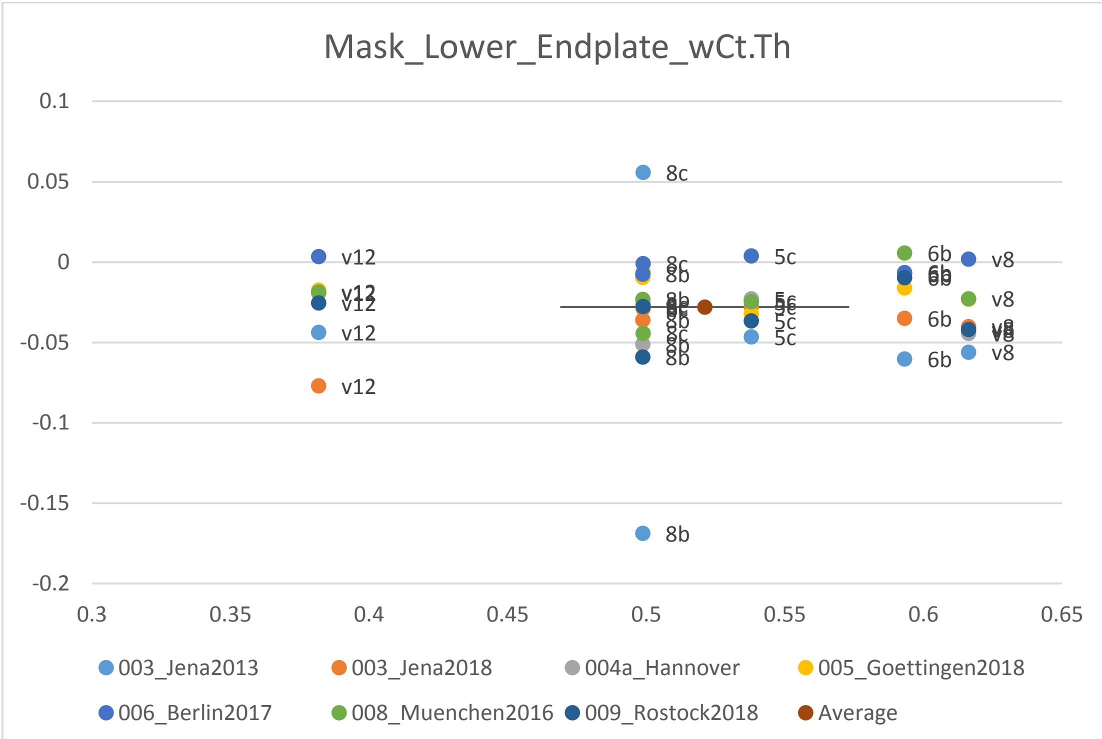

Mask_Cortex_Ct.Th-SD
0.12
0.1
0.08
0.06
0.04
0.02
0
-0.02
-0.04
0.39
0.4
0.41
0.42
0.43
0.44
0.45
0.46
0.47
8c
v12
5c
8b
v8
003_Jena2013
003_Jena2018
004a_Hannover
005_Goettingen2018
006_Berlin2017
008_Muenchen2016
009_Rostock2018
Average

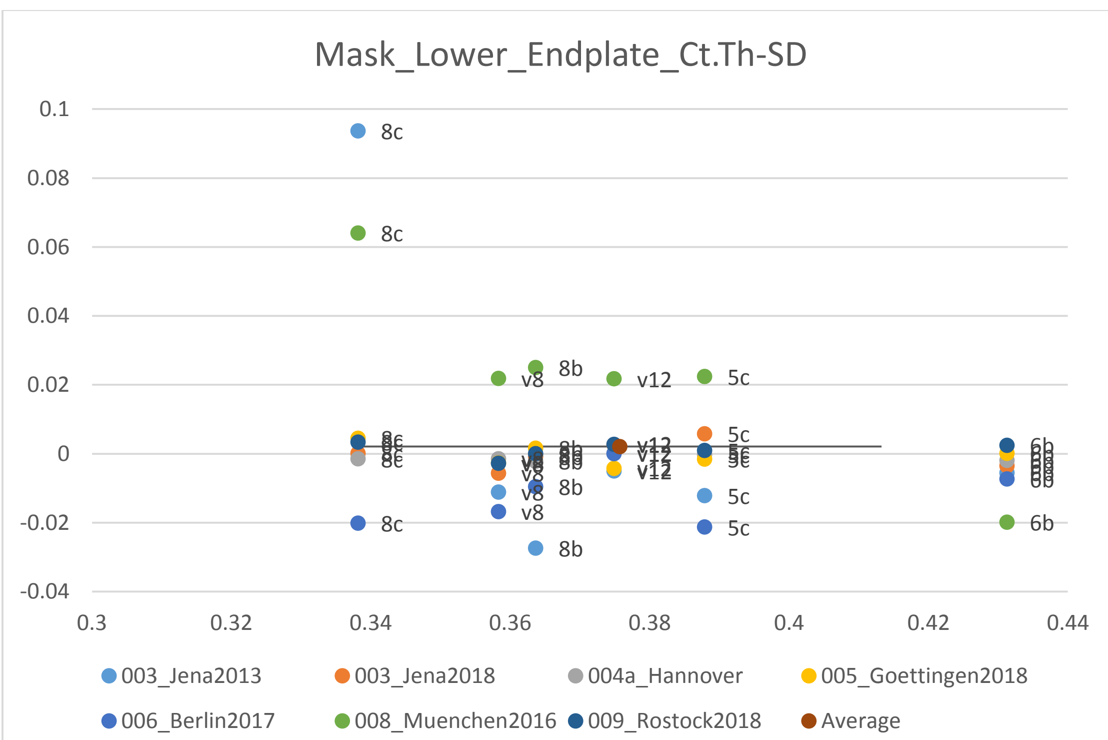

Mask_Cortex_TV
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
6
6.5
7
7.5
8
8.5
9
9.5
8c
v12
5c
8b
003_Jena2013
003_Jena2018
004a_Hannover
005_Goettingen2018
006_Berlin2017
008_Muenchen2016
009_Rostock2018
Average

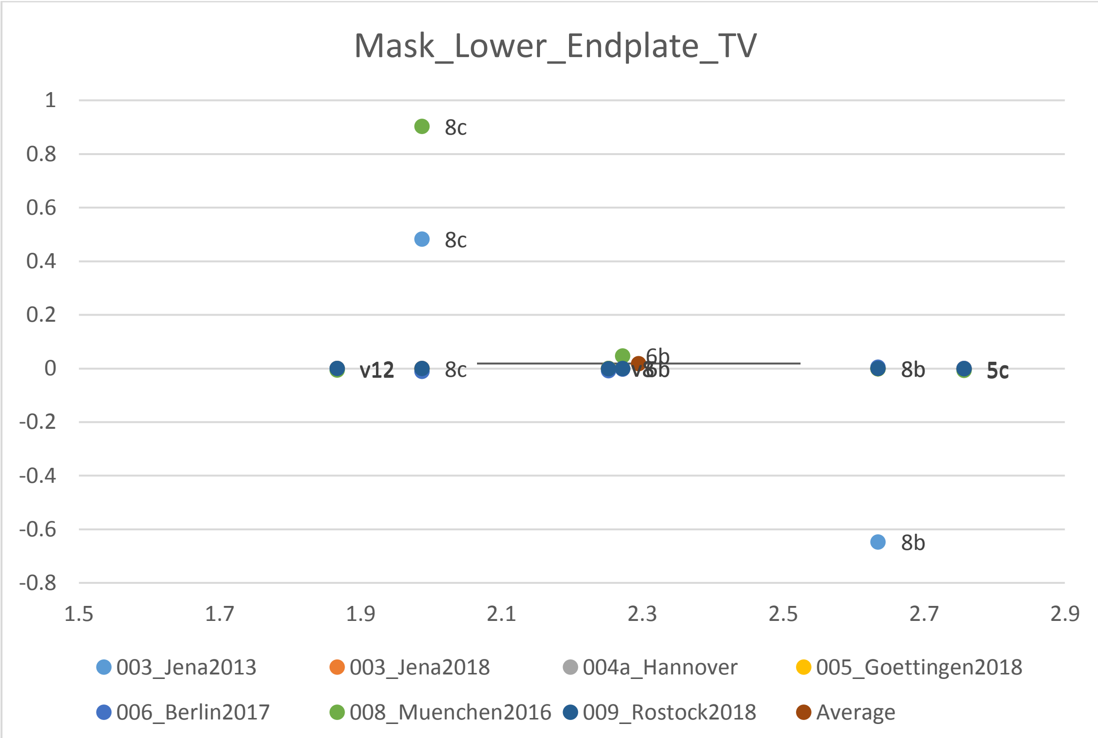


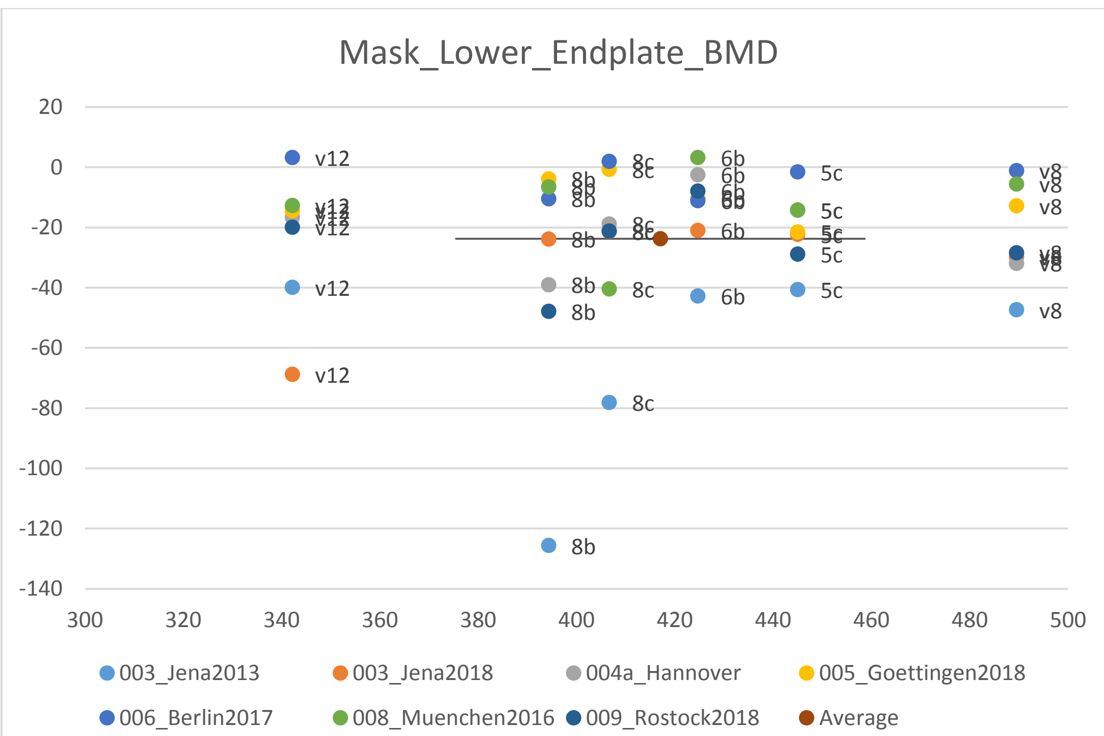
- **Lower_Endplate:**



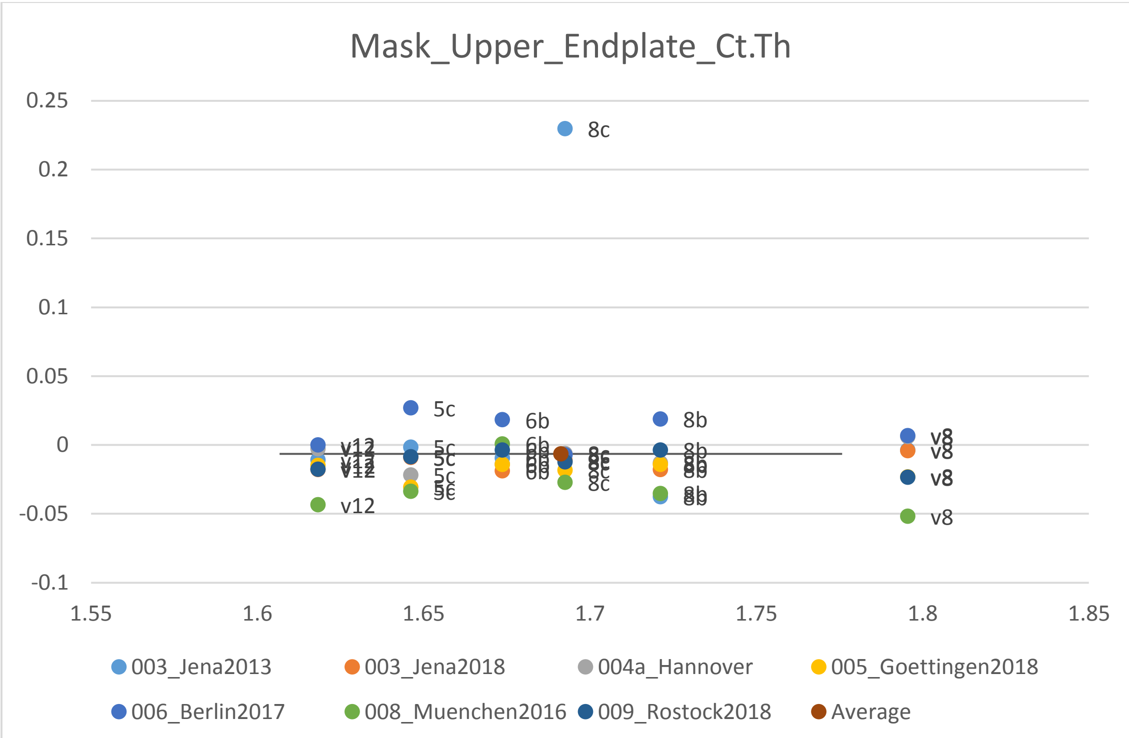

Mask_Lower_Endplate_wCt.Th
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
0.3
0.35
0.4
0.45
0.5
0.55
0.6
0.65
v12
8c
8b
5c
6b
v8
003_Jena2013
003_Jena2018
004a_Hannover
005_Goettingen2018
006_Berlin2017
008_Muenchen2016
009_Rostock2018
Average

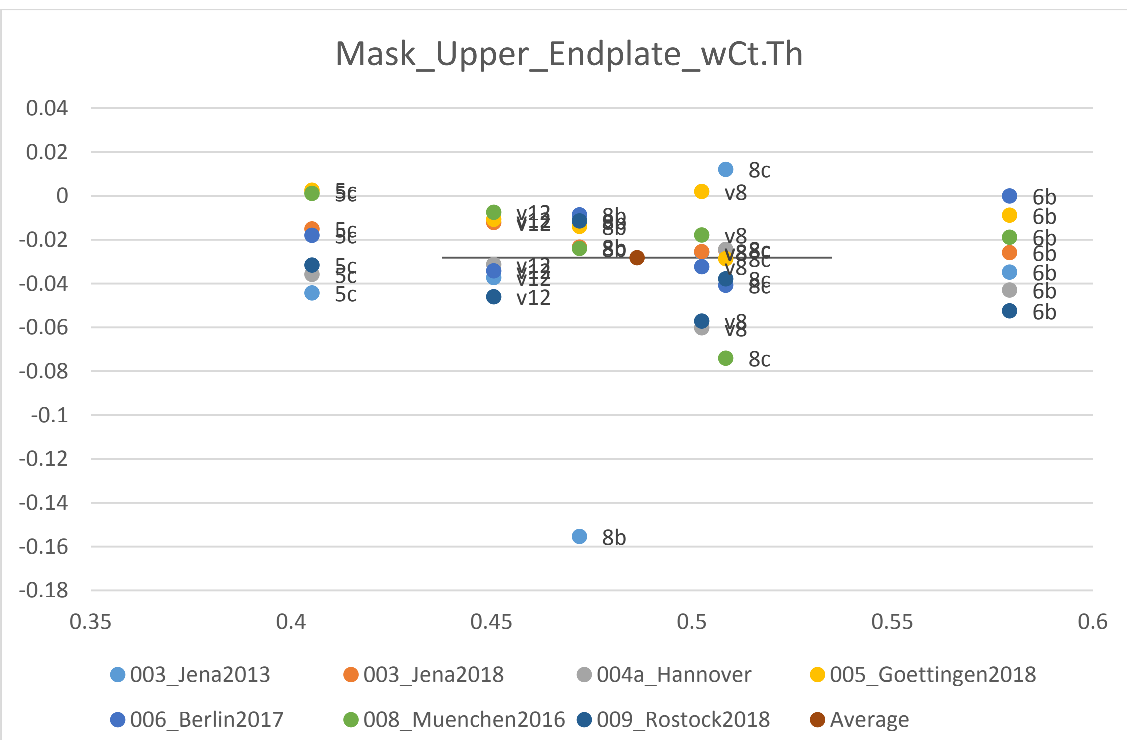

Mask_Lower_Endplate_Ct.Th-SD
0.1
0.08
0.06
0.04
0.02
0
-0.02
-0.04
0.3
0.32
0.34
0.36
0.38
0.4
0.42
0.44
8c
8b
v8
v12
5c
6b
003_Jena2013
003_Jena2018
004a_Hannover
005_Goettingen2018
006_Berlin2017
008_Muenchen2016
009_Rostock2018
Average

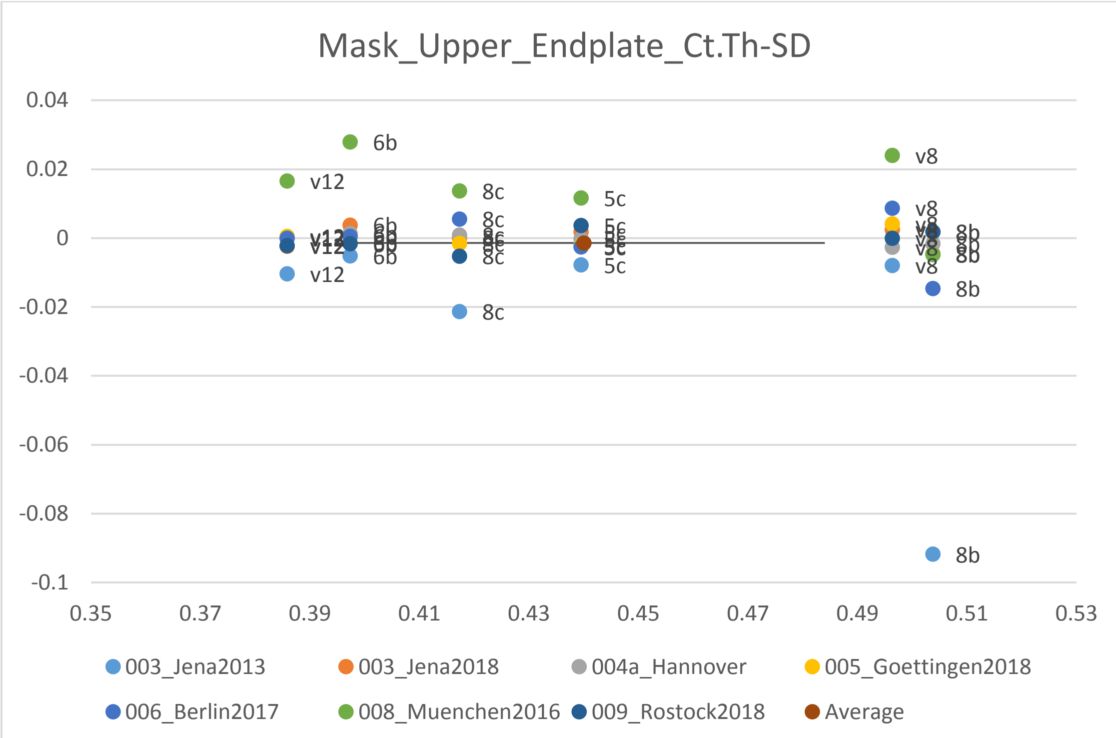

Mask_Lower_Endplate_TV
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
1.5
1.7
1.9
2.1
2.3
2.5
2.7
2.9
8c
8c
v12
8c
6b
8b
5c
8b
003_Jena2013
003_Jena2018
004a_Hannover
005_Goettingen2018
006_Berlin2017
008_Muenchen2016
009_Rostock2018
Average

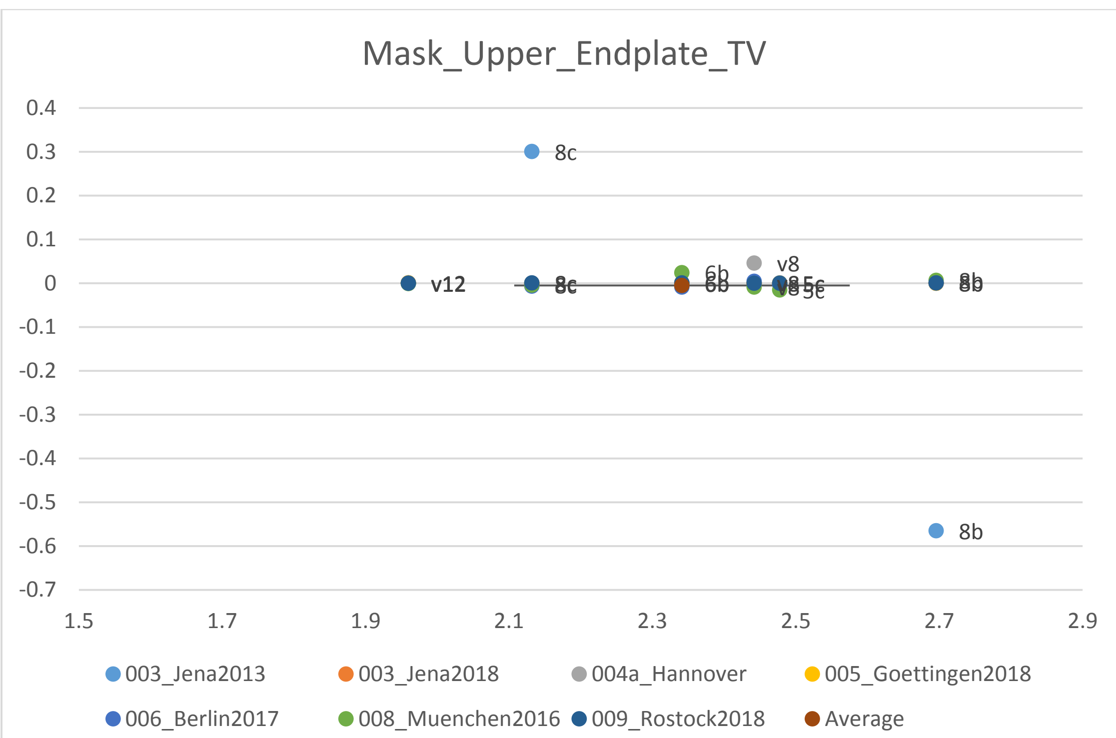

Mask_Lower_Endplate_BMD
20
0
-20
-40
-60
-80
-100
-120
-140
300
320
340
360
380
400
420
440
460
480
500
v12
8c
6b
5c
v8
8b
8b
v12
8c
6b
5c
v8
8b
v12
6b
5c
v12
8c
8c
8b
v12
8b
8c
6b
5c
v8
8b
v12
8c
8b
003_Jena2013
003_Jena2018
004a_Hannover
005_Goettingen2018
006_Berlin2017
008_Muenchen2016
009_Rostock2018
Average

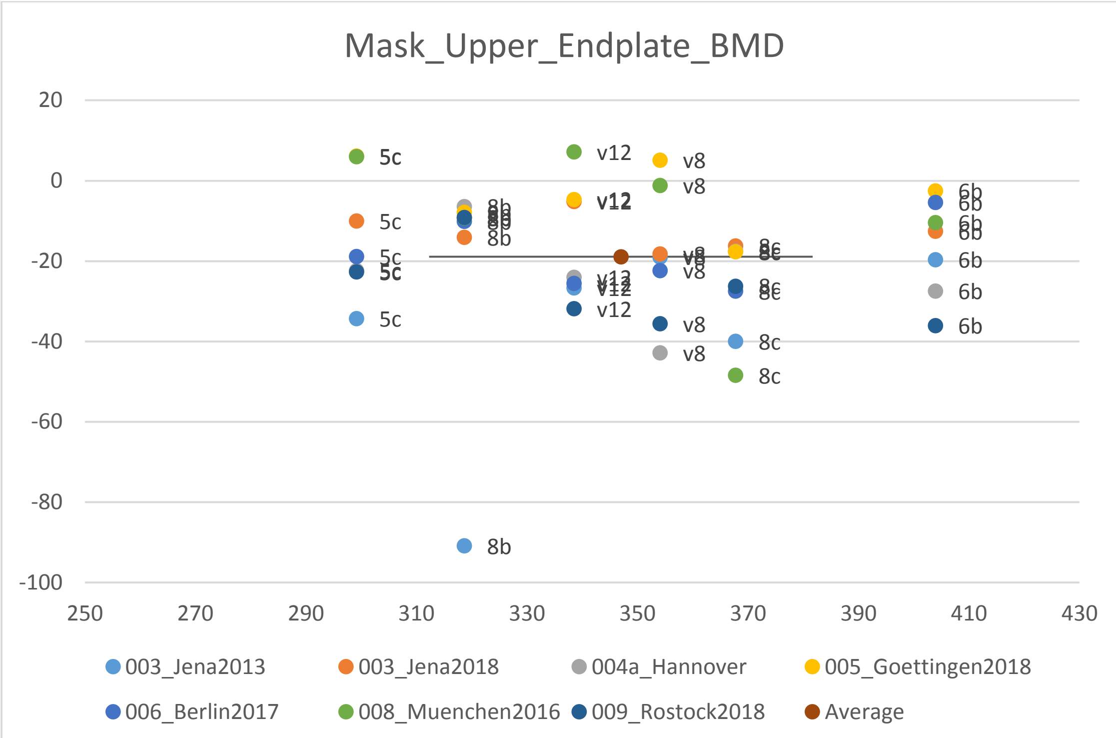
- **Upper_Endplate:**



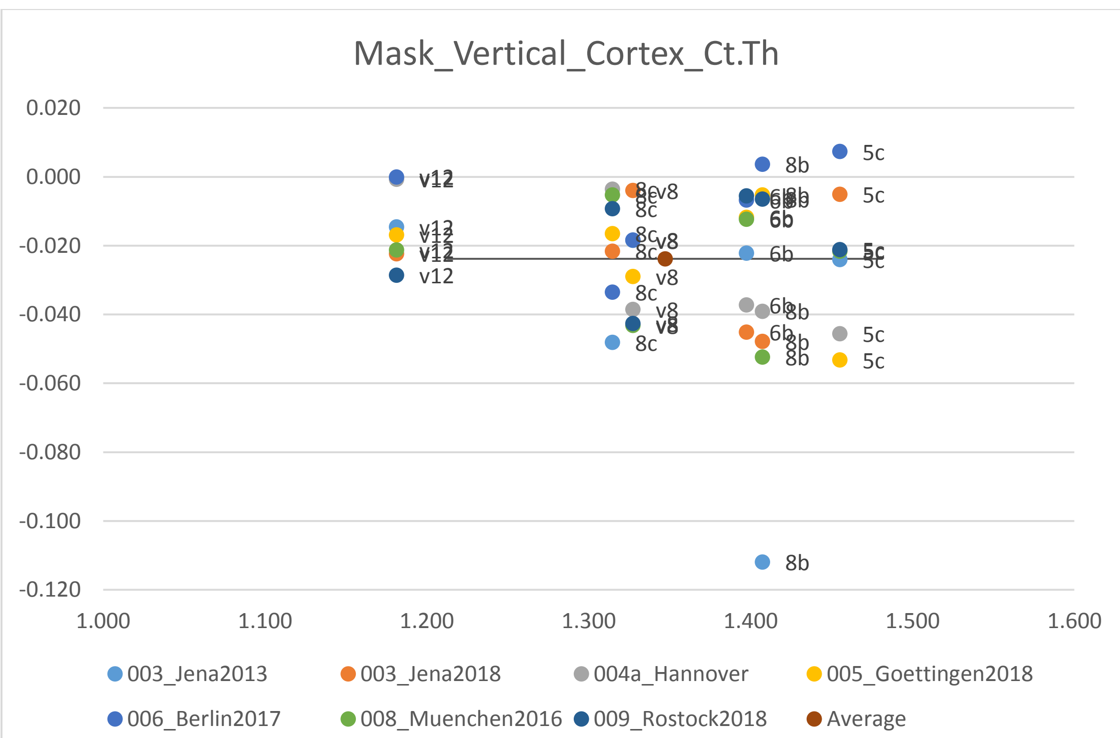


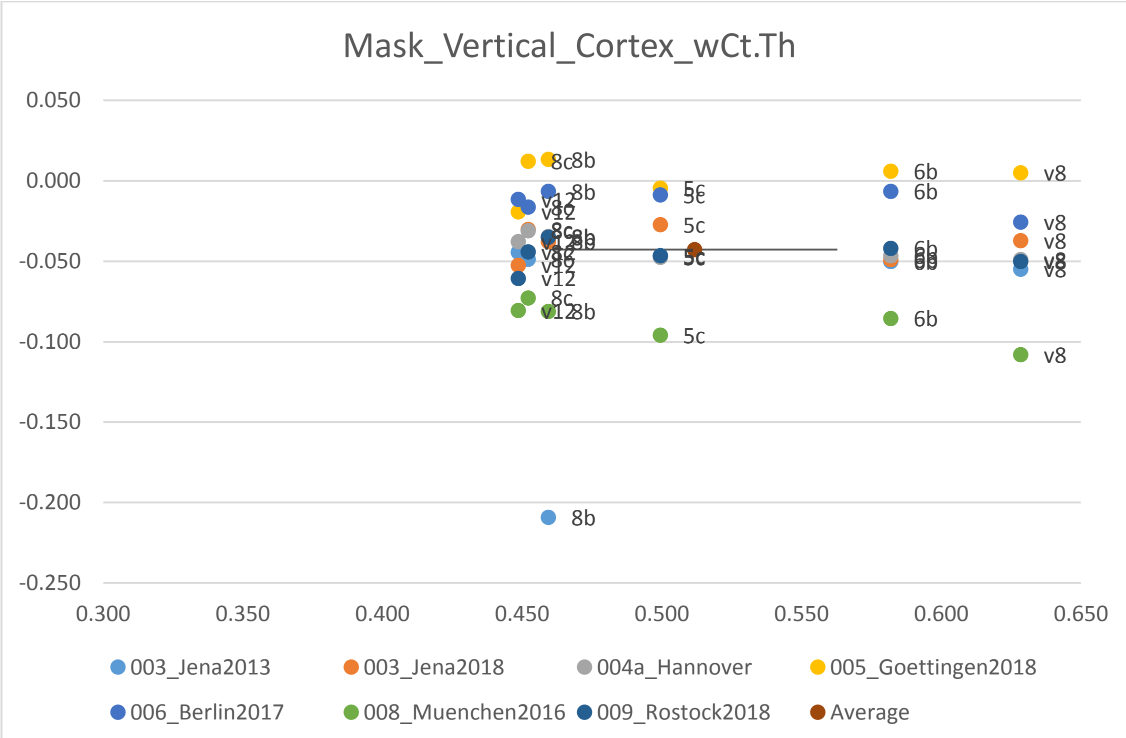

Mask_Upper_Endplate_Ct.Th-SD
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
-0.1
0.35
0.37
0.39
0.41
0.43
0.45
0.47
0.49
0.51
0.53
6b
v12
8c
5c
v8
8b
003_Jena2013
003_Jena2018
004a_Hannover
005_Goettingen2018
006_Berlin2017
008_Muenchen2016
009_Rostock2018
Average

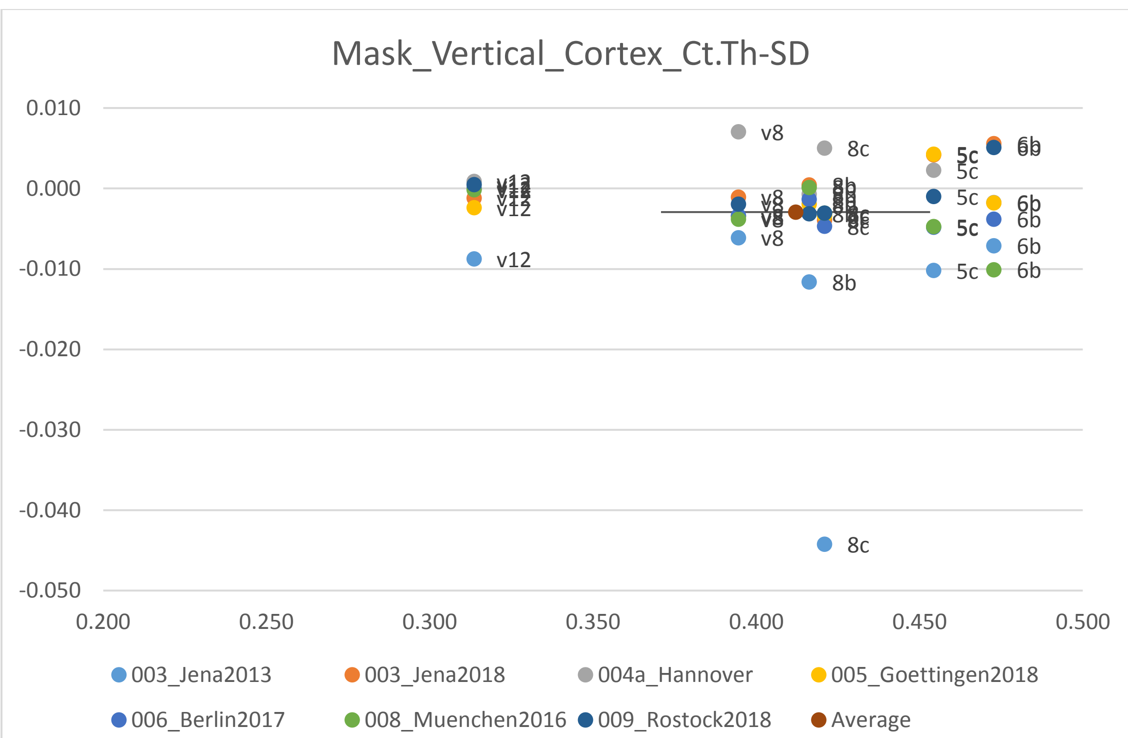

Mask_Upper_Endplate_TV
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
1.5
1.7
1.9
2.1
2.3
2.5
2.7
2.9
8c
v12
6b
v8
5c
8b
003_Jena2013
003_Jena2018
004a_Hannover
005_Goettingen2018
006_Berlin2017
008_Muenchen2016
009_Rostock2018
Average

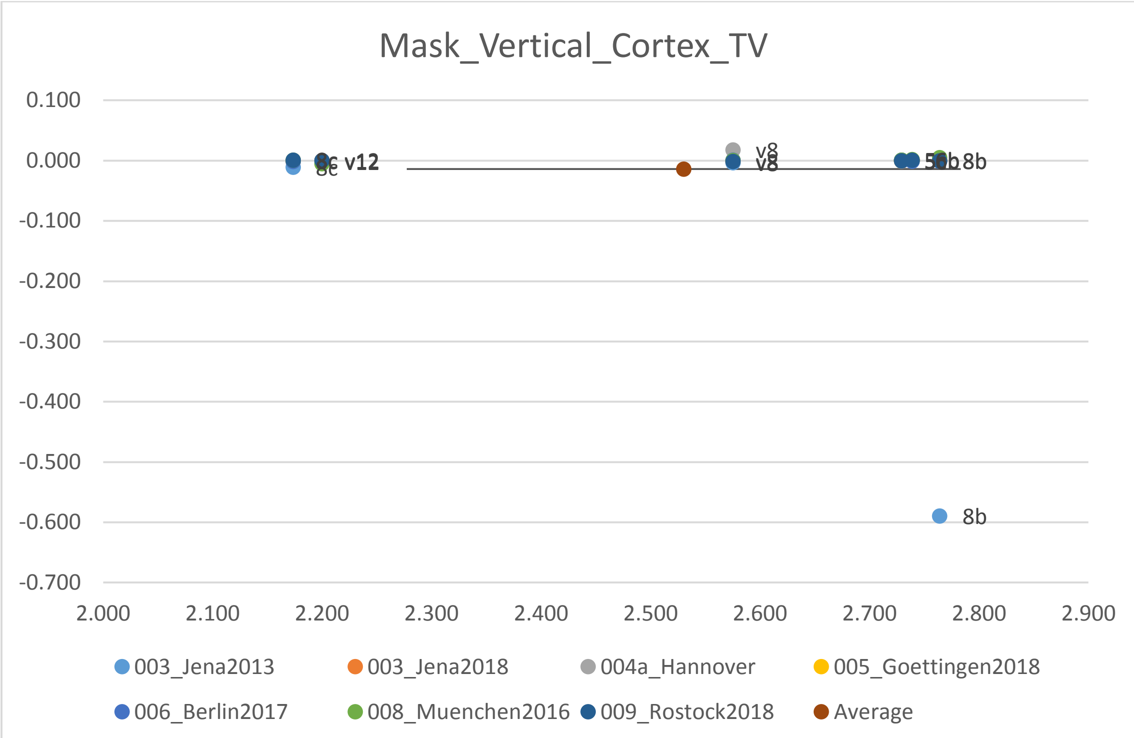


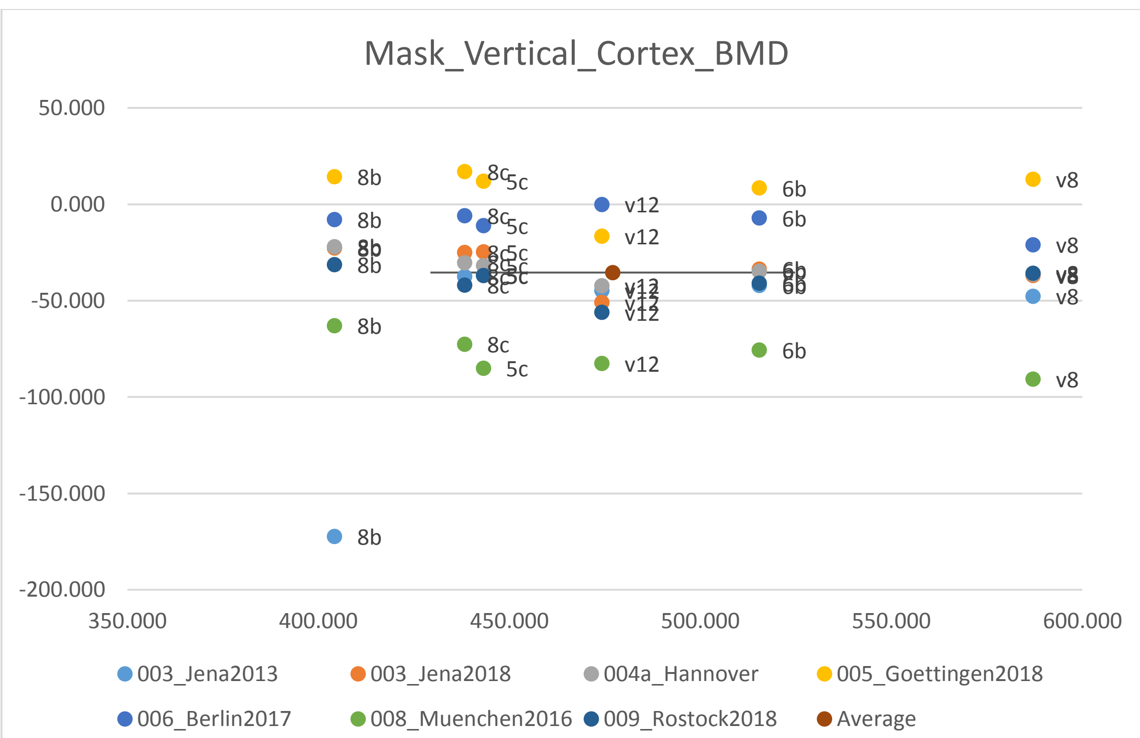
- ○ **Vertical_Cortex:**




Mask_Vertical_Cortex_wCt.Th
0.050
0.000
-0.050
-0.100
-0.150
-0.200
-0.250
0.300
0.350
0.400
0.450
0.500
0.550
0.600
0.650
003_Jena2013
003_Jena2018
004a_Hannover
005_Goettingen2018
006_Berlin2017
008_Muenchen2016
009_Rostock2018
Average

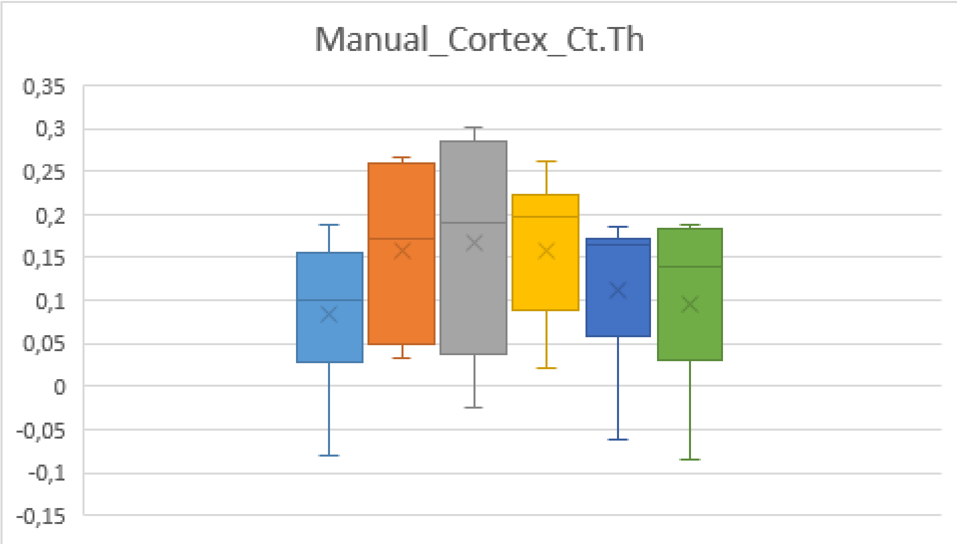

Mask_Vertical_Cortex_Ct.Th-SD
0.010
0.000
-0.010
-0.020
-0.030
-0.040
-0.050
0.200
0.250
0.300
0.350
0.400
0.450
0.500
003_Jena2013
003_Jena2018
004a_Hannover
005_Goettingen2018
006_Berlin2017
008_Muenchen2016
009_Rostock2018
Average

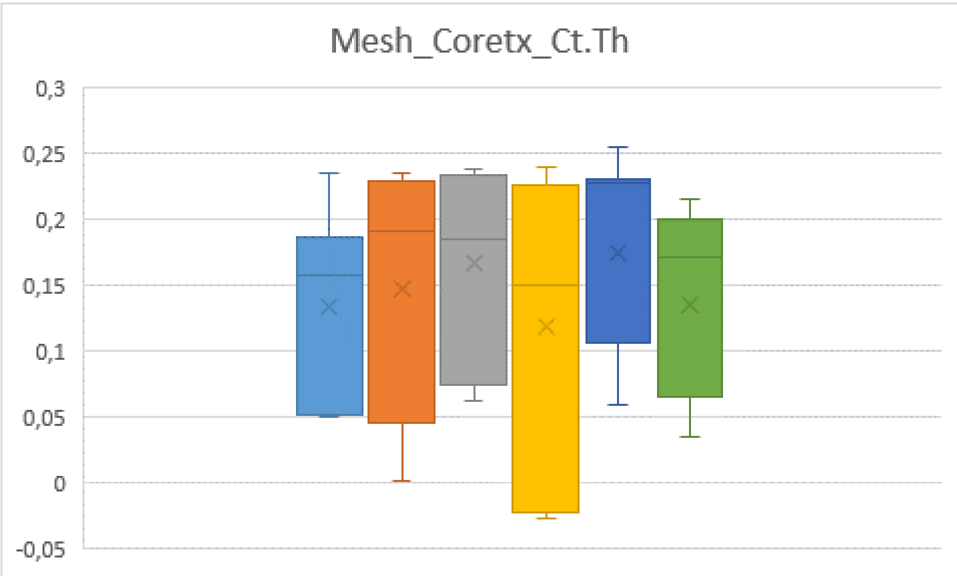

Mask_Vertical_Cortex_TV
0.100
0.000
-0.100
-0.200
-0.300
-0.400
-0.500
-0.600
-0.700
2.000
2.100
2.200
2.300
2.400
2.500
2.600
2.700
2.800
2.900
8c
v12
v8
5c
6b
8b
003_Jena2013
003_Jena2018
004a_Hannover
005_Goettingen2018
006_Berlin2017
008_Muenchen2016
009_Rostock2018
Average

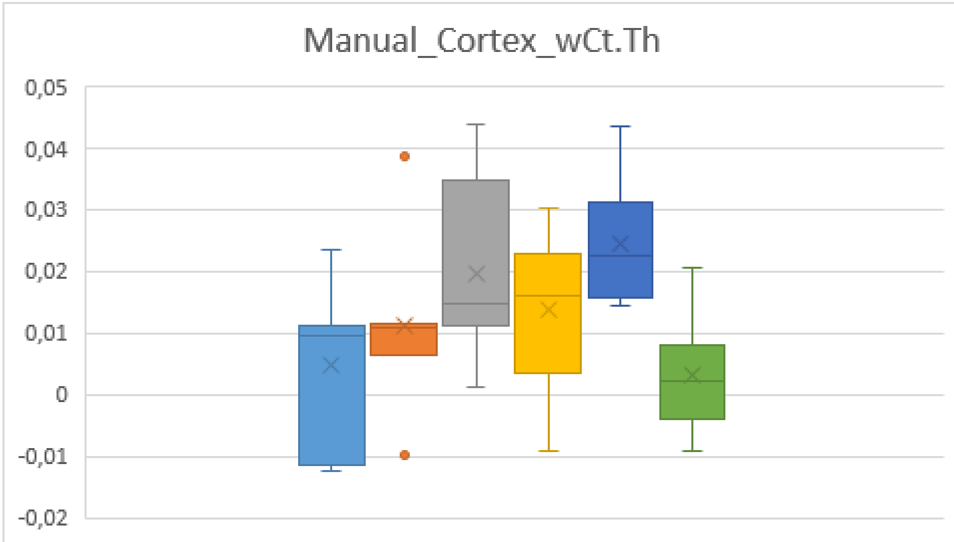

Mask_Vertical_Cortex_BMD
50.000
0.000
-50.000
-100.000
-150.000
-200.000
350.000
400.000
450.000
500.000
550.000
600.000
8b
8c
5c
v12
6b
v8
003_Jena2013
003_Jena2018
004a_Hannover
005_Goettingen2018
006_Berlin2017
008_Muenchen2016
009_Rostock2018
Average

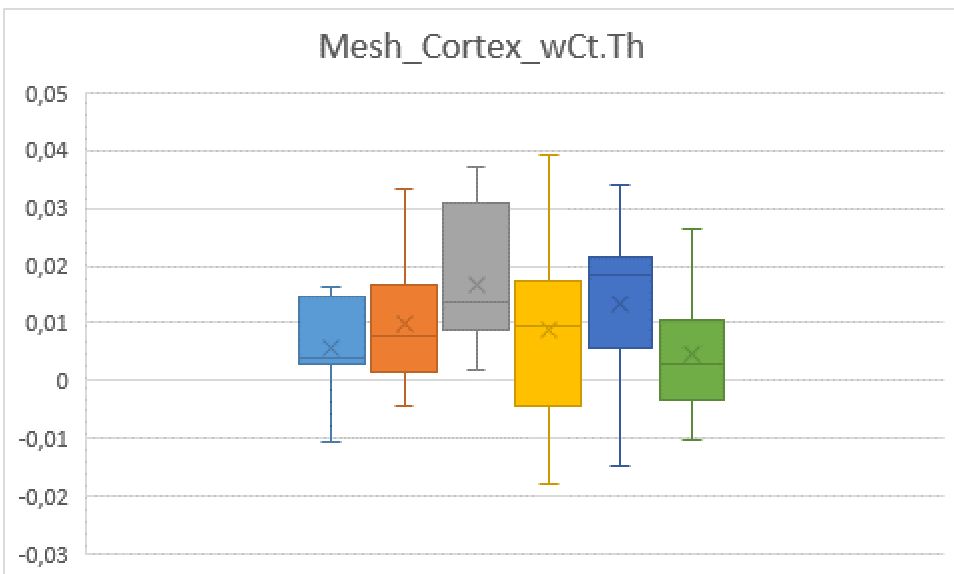
11. Appendix D

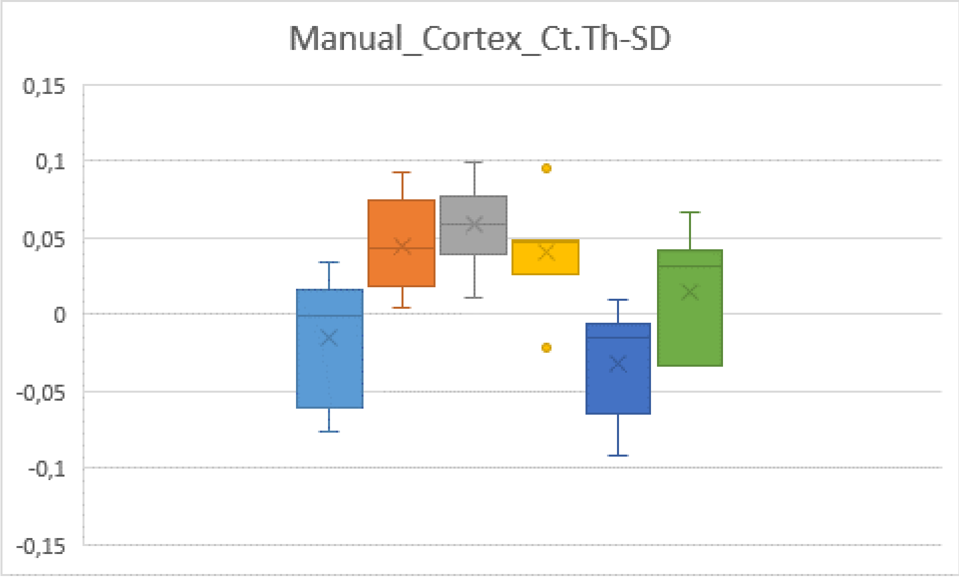
- **Cortex:**

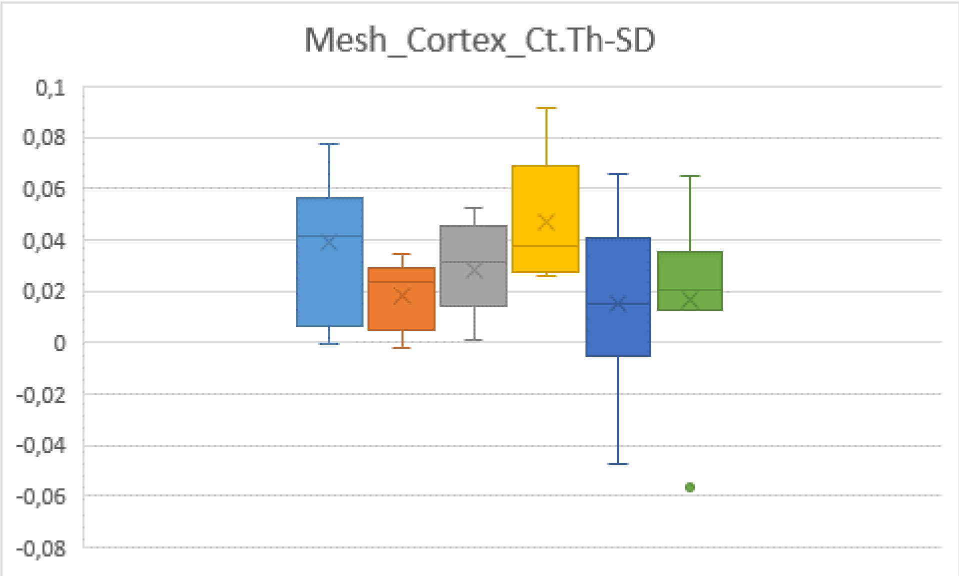


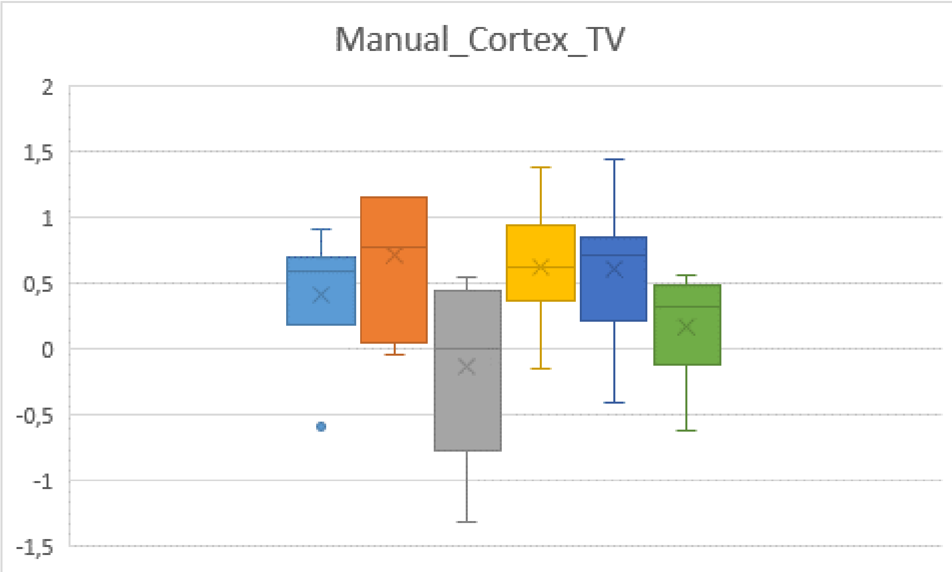


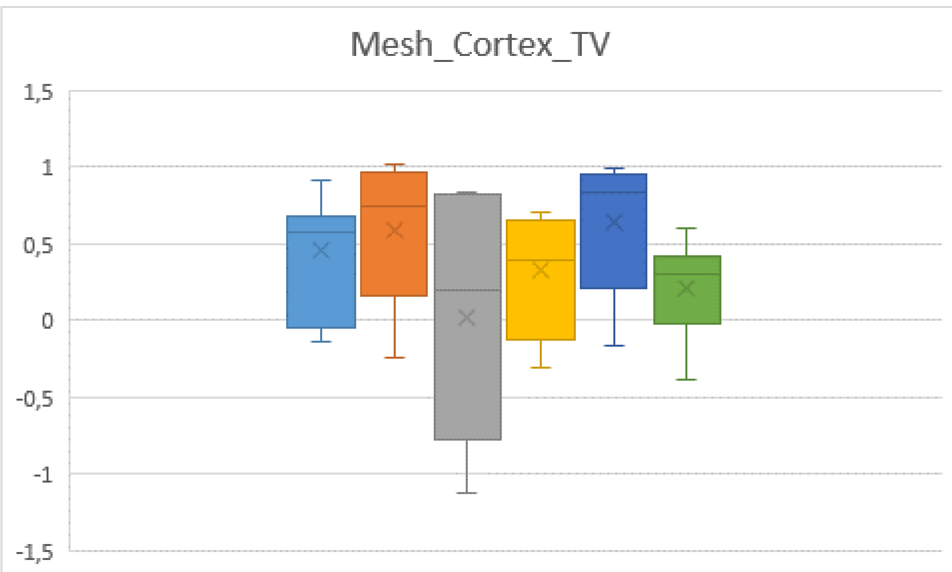

Manual_Cortex_wCt.Th
0,05
0,04
0,03
0,02
0,01
0
-0,01
-0,02

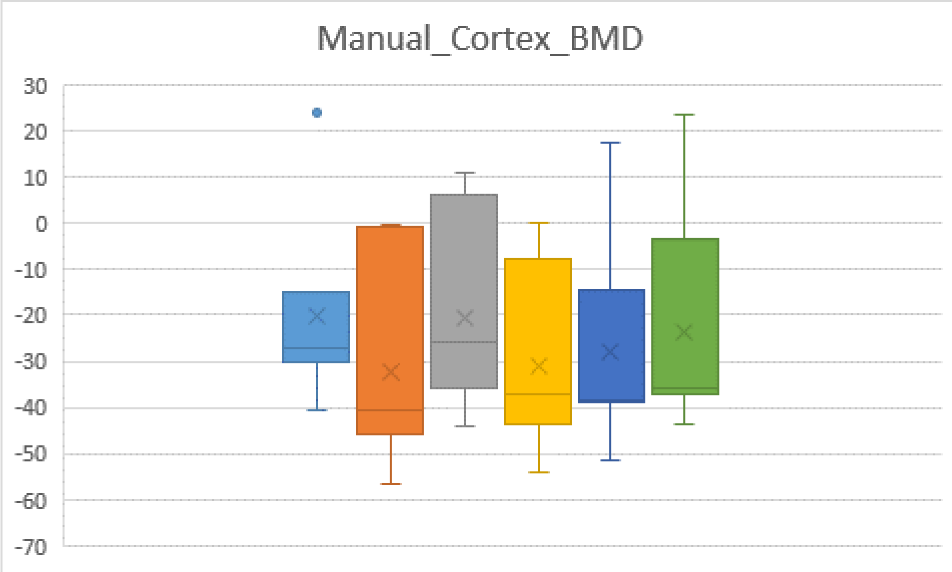

Mesh_Cortex_wCt.Th
0,05
0,04
0,03
0,02
0,01
0
-0,01
-0,02
-0,03

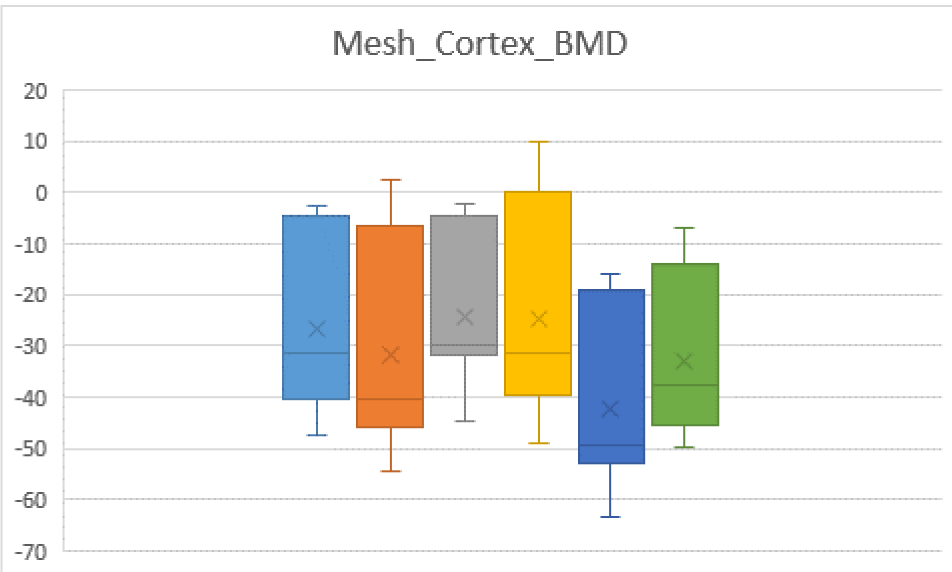

Manual_Cortex_Ct.Th-SD
0,15
0,1
0,05
0
-0,05
-0,1
-0,15


Mesh_Cortex_Ct.Th-SD
0,1
0,08
0,06
0,04
0,02
0
-0,02
-0,04
-0,06
-0,08

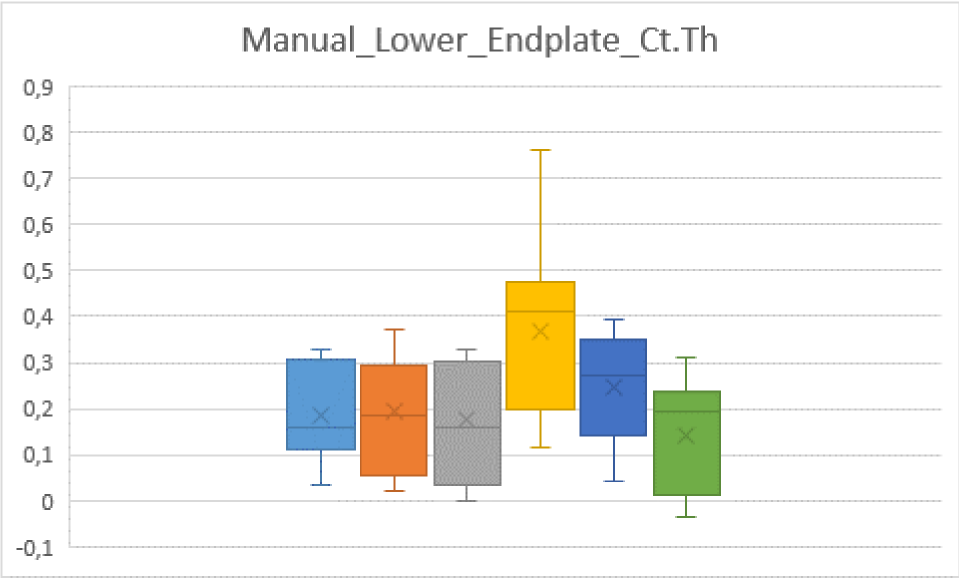

Manual_Cortex_TV
2
1,5
1
0,5
0
-0,5
-1
-1,5

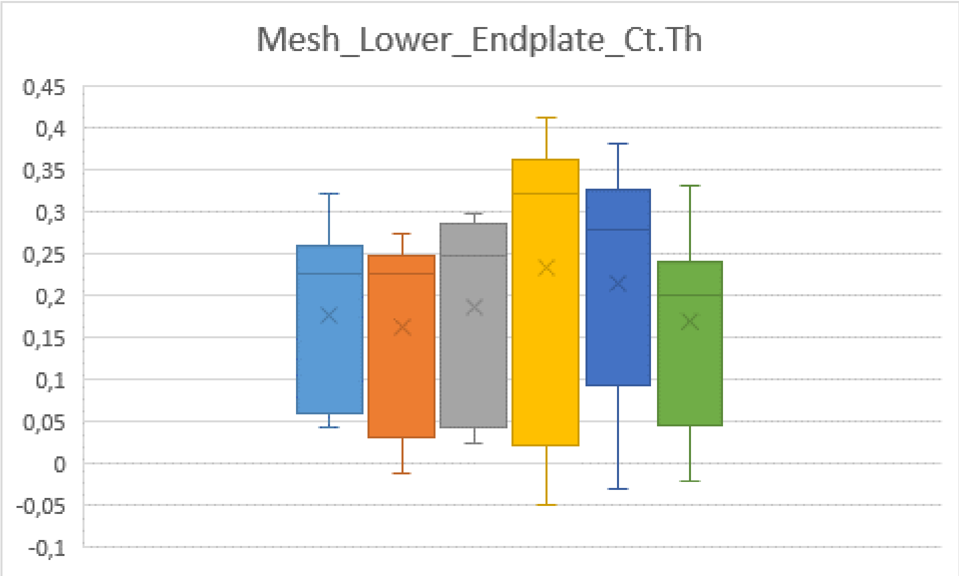

Mesh_Cortex_TV
1,5
1
0,5
0
-0,5
-1
-1,5

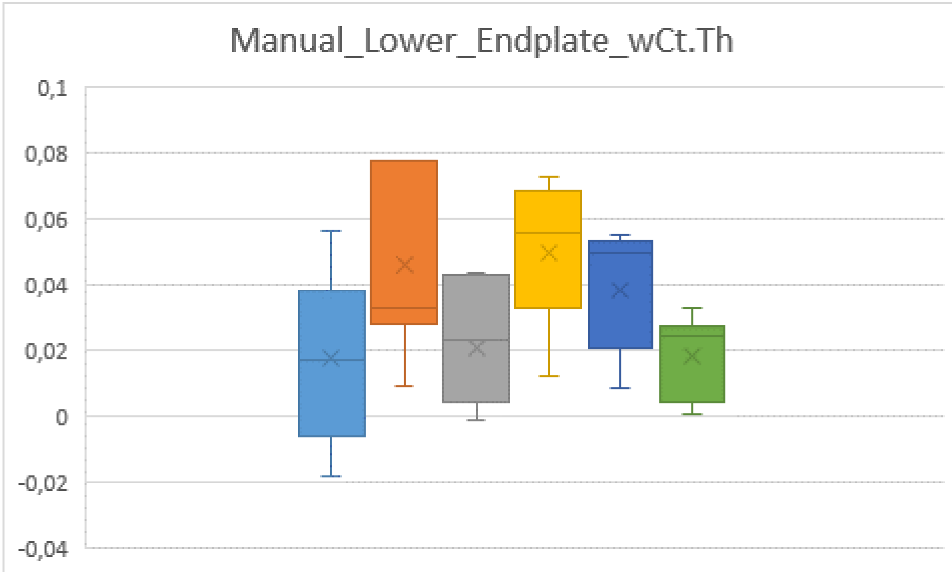

Manual_Cortex_BMD
30
20
10
0
-10
-20
-30
-40
-50
-60
-70

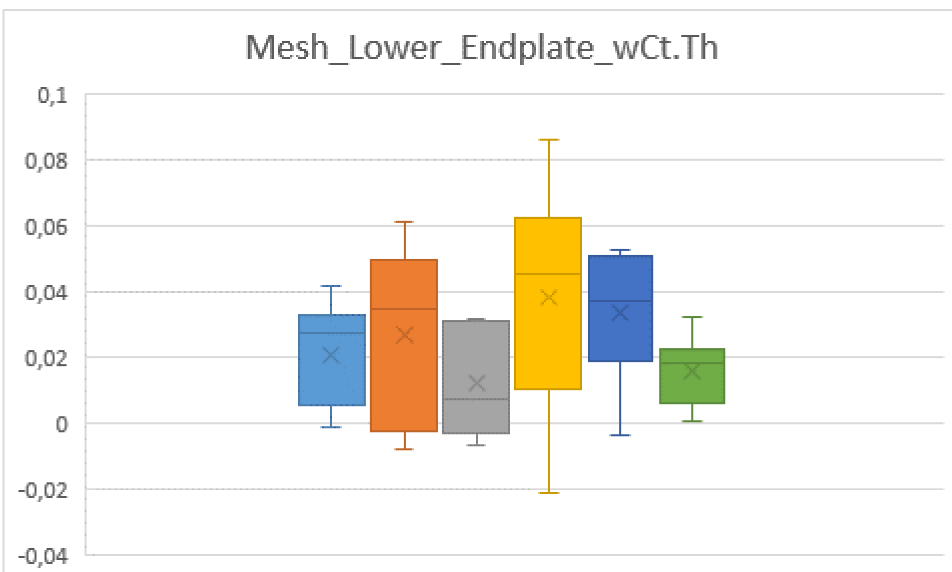

Mesh_Cortex_BMD
20
10
0
-10
-20
-30
-40
-50
-60
-70

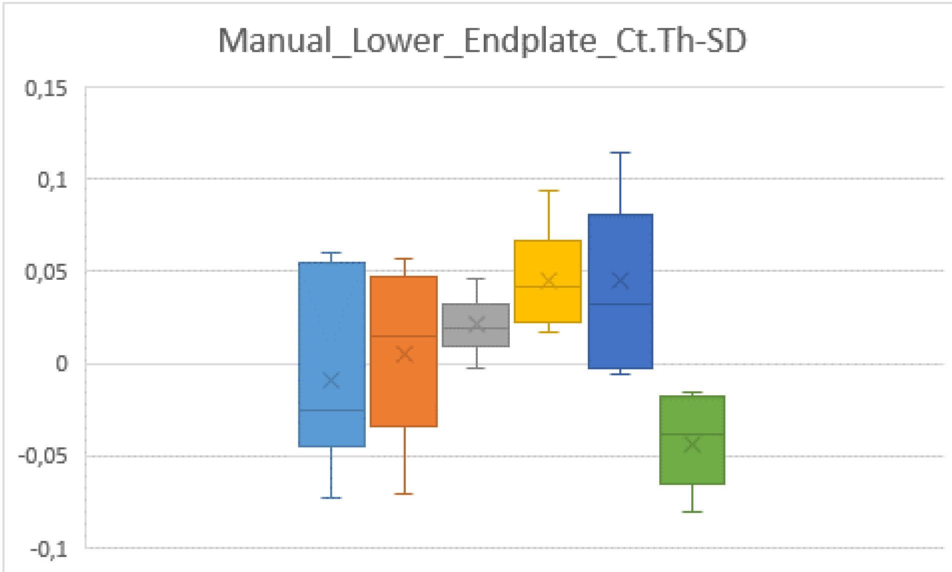
- **Lower_Endplate:**

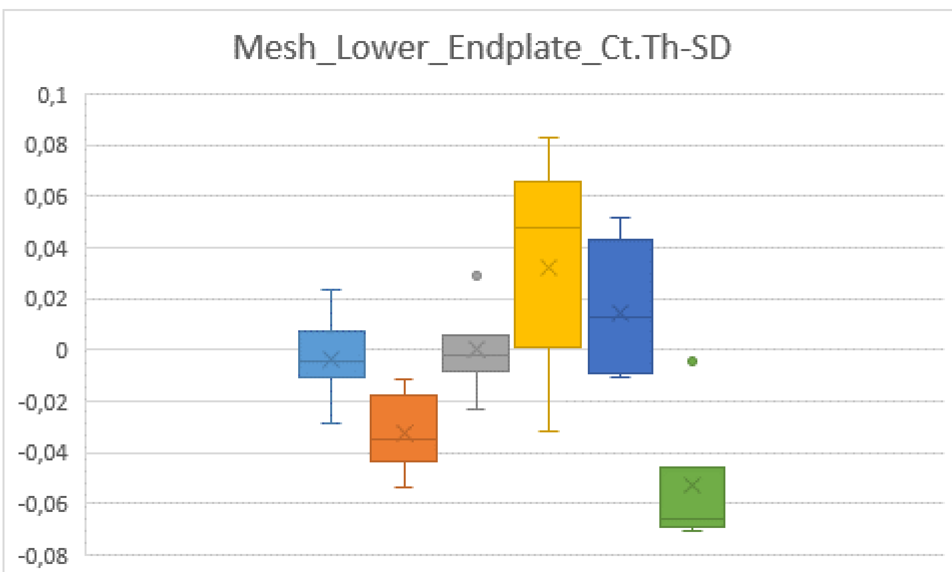


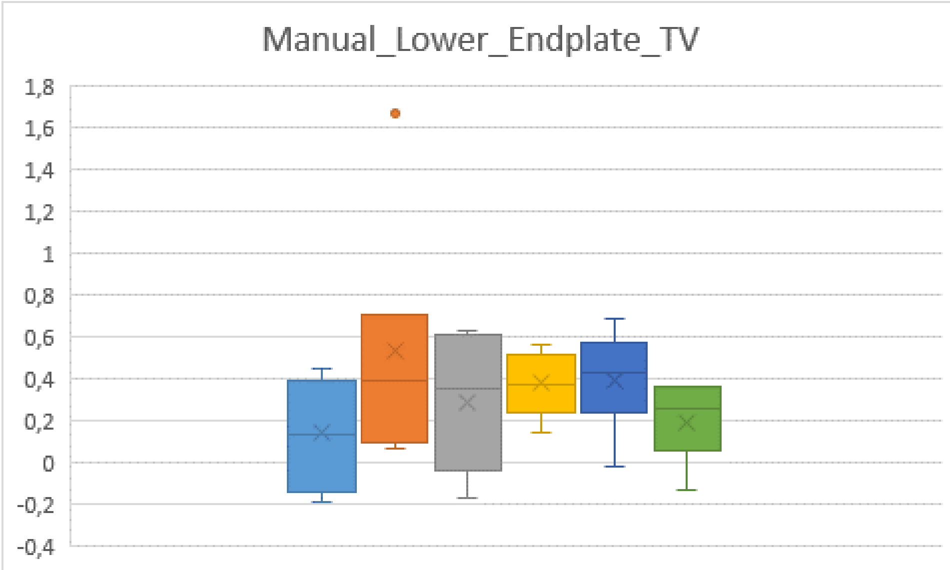


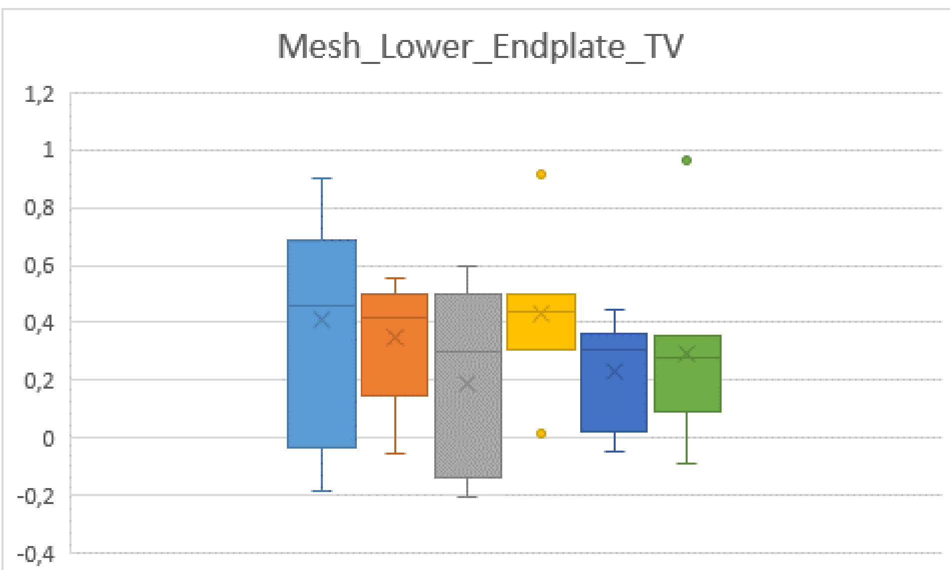

Manual_Lower_Endplate_wCt.Th
0,1
0,08
0,06
0,04
0,02
0
-0,02
-0,04

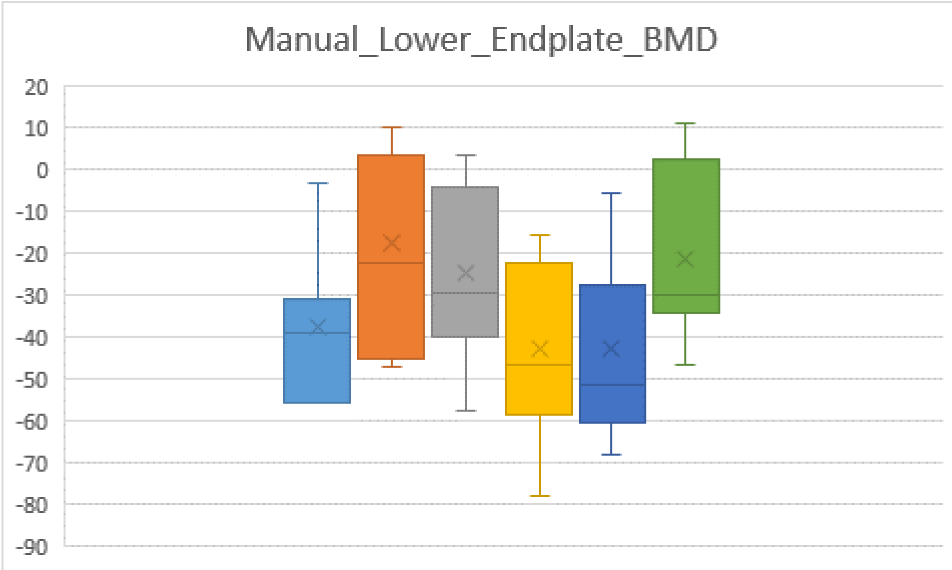

Mesh_Lower_Endplate_wCt.Th
0,1
0,08
0,06
0,04
0,02
0
-0,02
-0,04

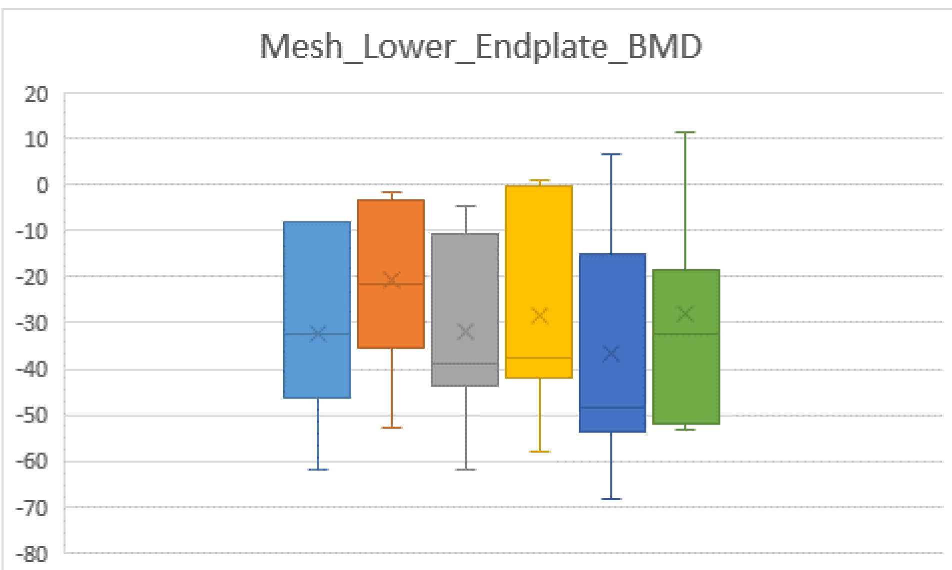

Manual_Lower_Endplate_Ct.Th-SD
0,15
0,1
0,05
0
-0,05
-0,1


Mesh_Lower_Endplate_Ct.Th-SD
0,1
0,08
0,06
0,04
0,02
0
-0,02
-0,04
-0,06
-0,08

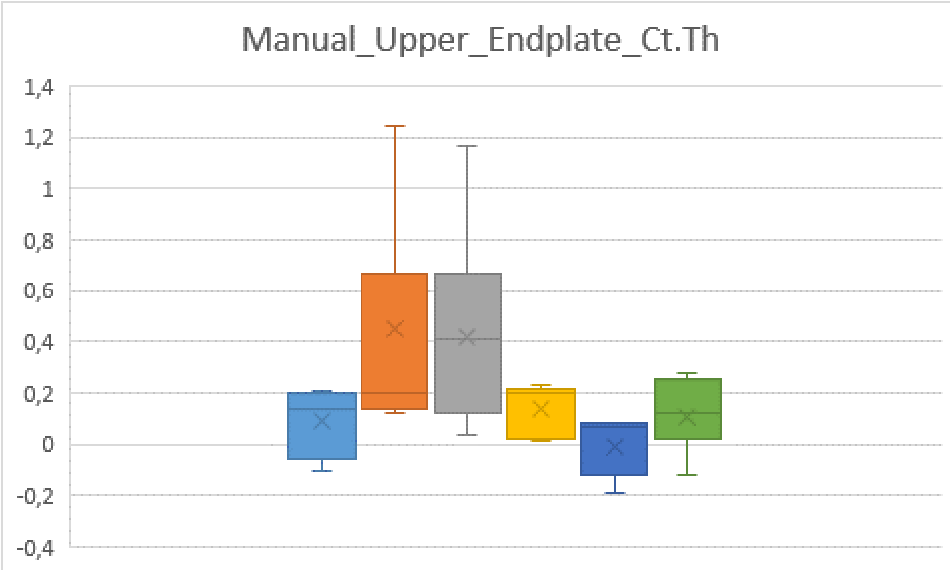

Manual_Lower_Endplate_TV
1,8
1,6
1,4
1,2
1
0,8
0,6
0,4
0,2
0
-0,2
-0,4

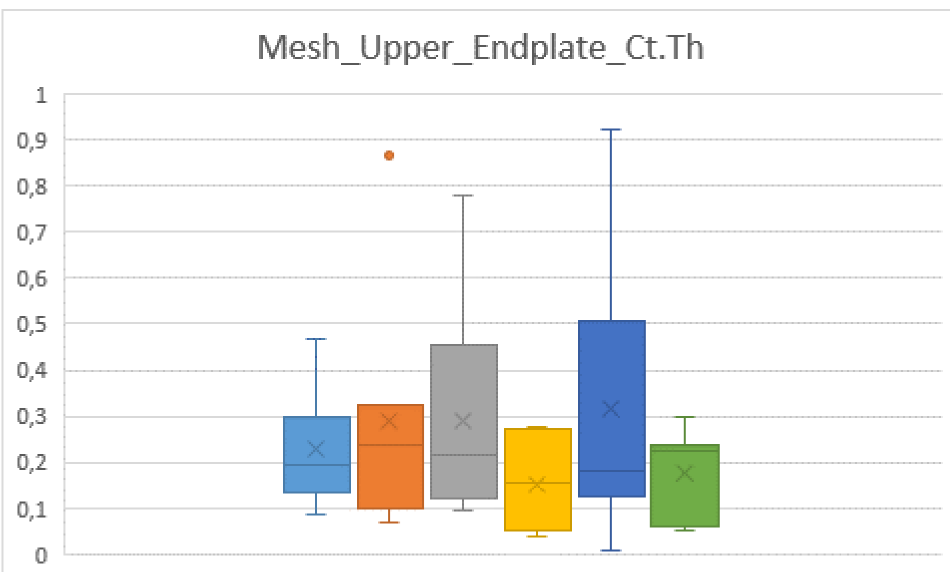

Mesh_Lower_Endplate_TV
1,2
1
0,8
0,6
0,4
0,2
0
-0,2
-0,4

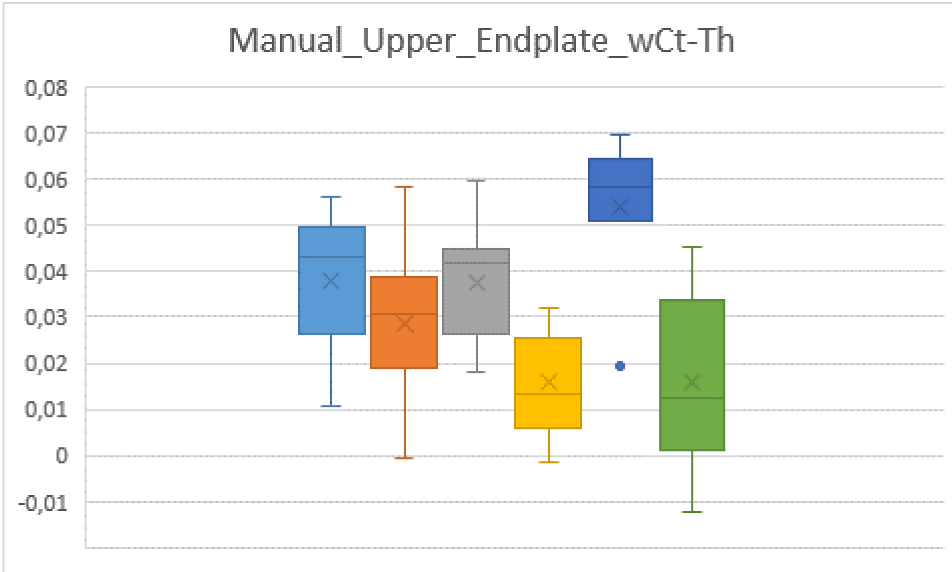

Manual_Lower_Endplate_BMD
20
10
0
-10
-20
-30
-40
-50
-60
-70
-80
-90

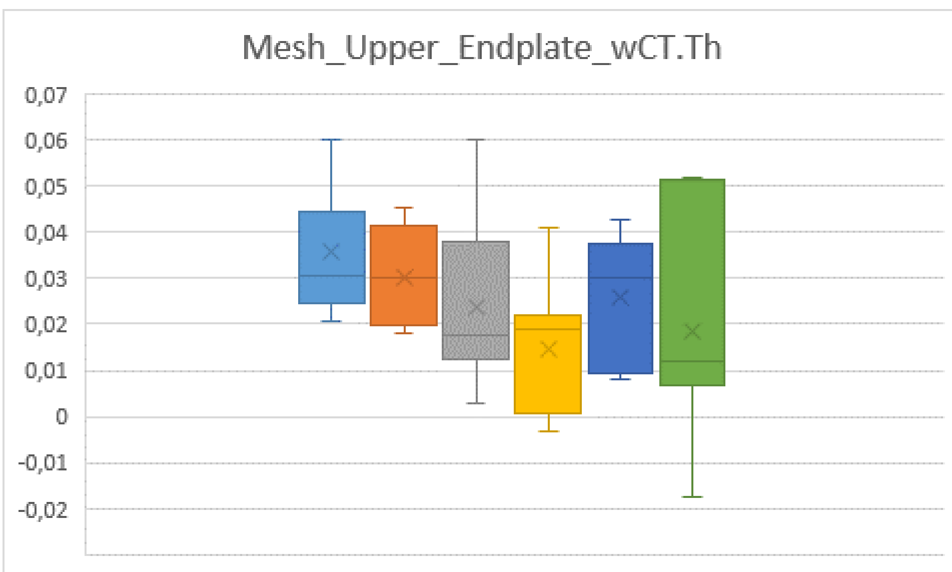

Mesh_Lower_Endplate_BMD
20
10
0
-10
-20
-30
-40
-50
-60
-70
-80

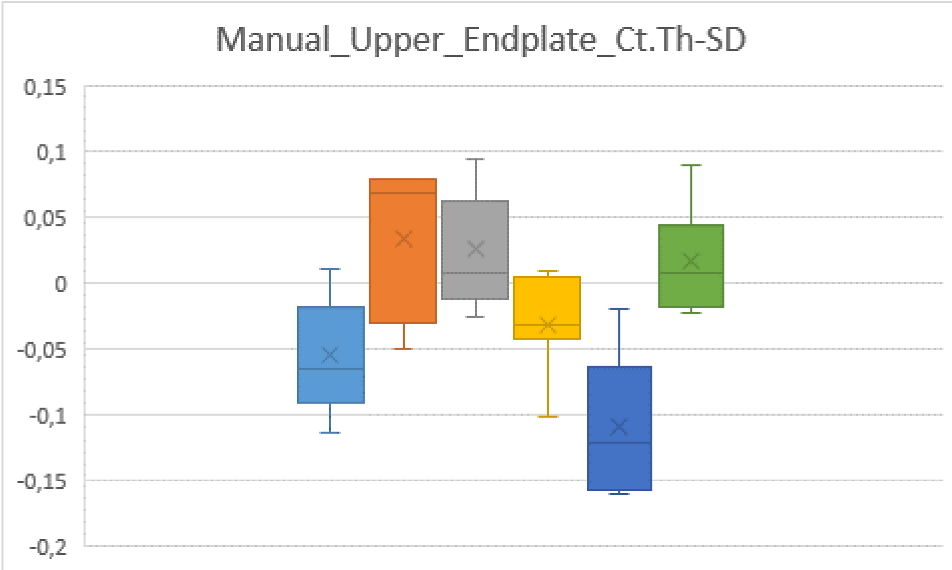
- **Upper_Endplate:**

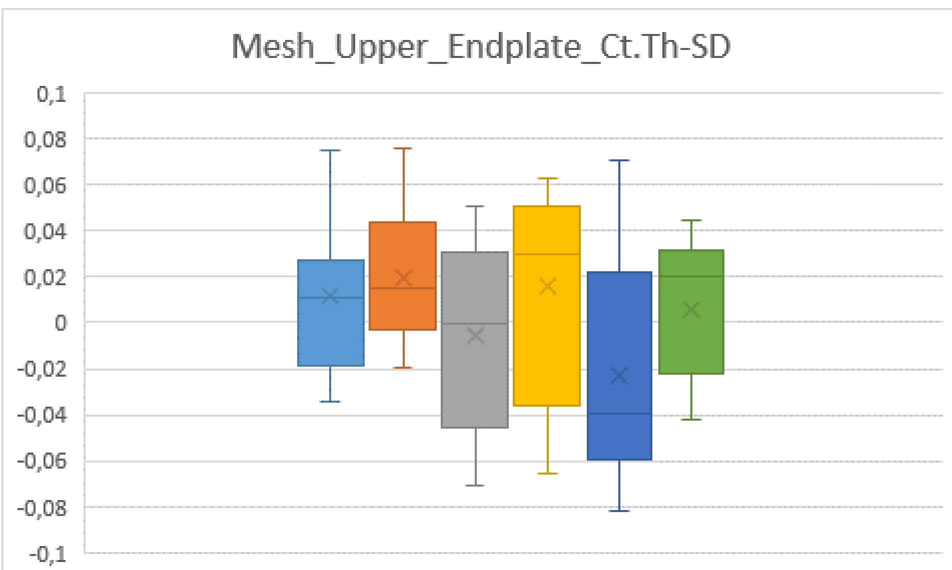


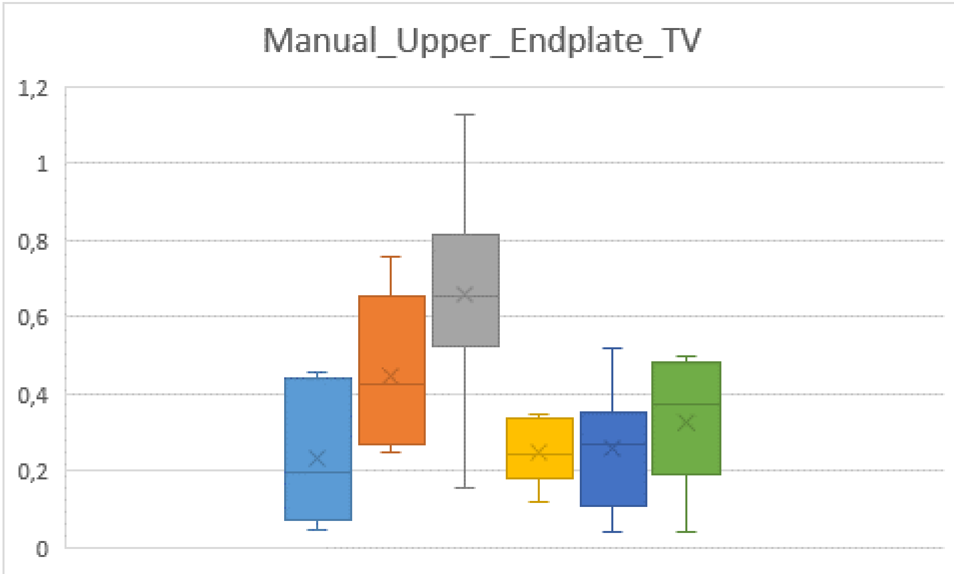


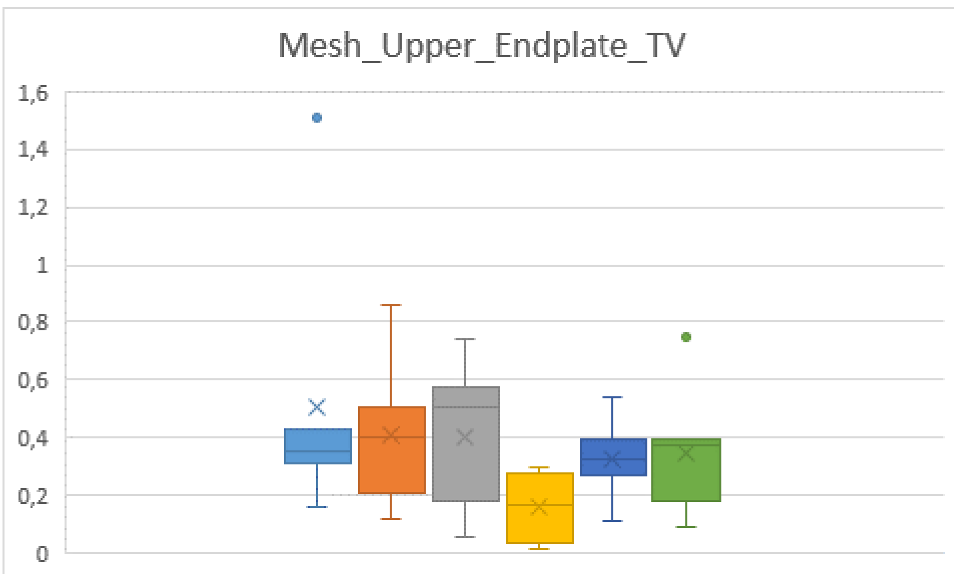

Manual_Upper_Endplate_wCt-Th
0,08
0,07
0,06
0,05
0,04
0,03
0,02
0,01
0
-0,01

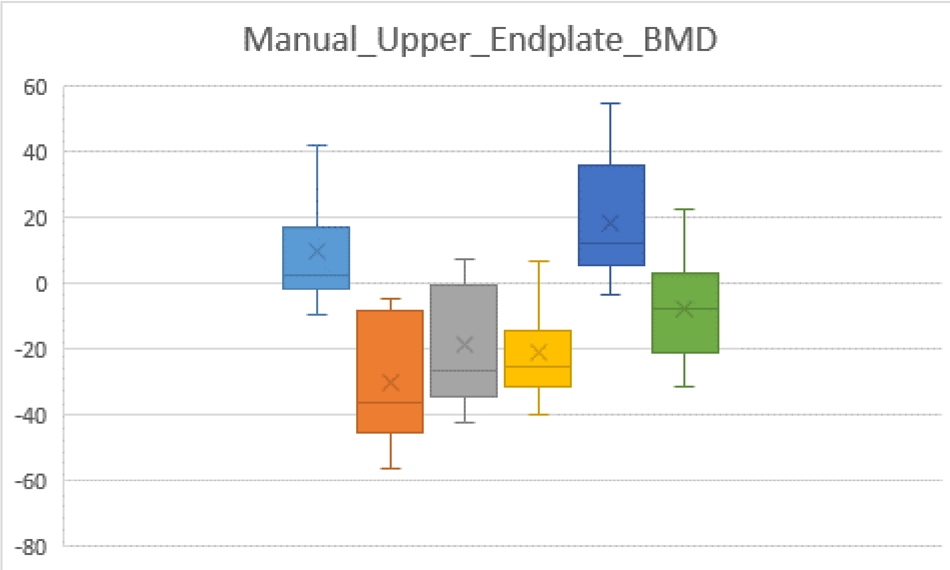

Mesh_Upper_Endplate_wCT.Th
0,07
0,06
0,05
0,04
0,03
0,02
0,01
0
-0,01
-0,02

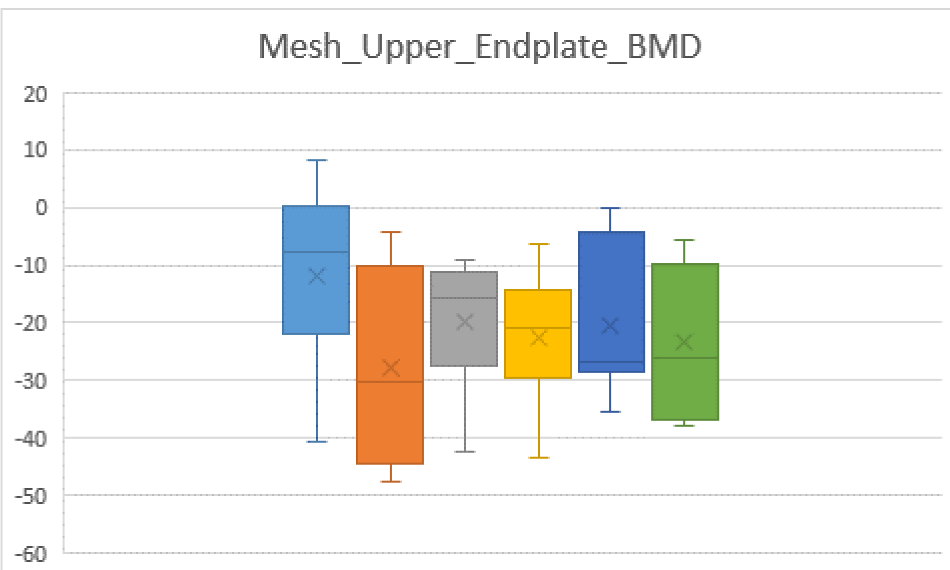

Manual_Upper_Endplate_Ct.Th-SD
0,15
0,1
0,05
0
-0,05
-0,1
-0,15
-0,2


Mesh_Upper_Endplate_Ct.Th-SD
0,1
0,08
0,06
0,04
0,02
0
-0,02
-0,04
-0,06
-0,08
-0,1

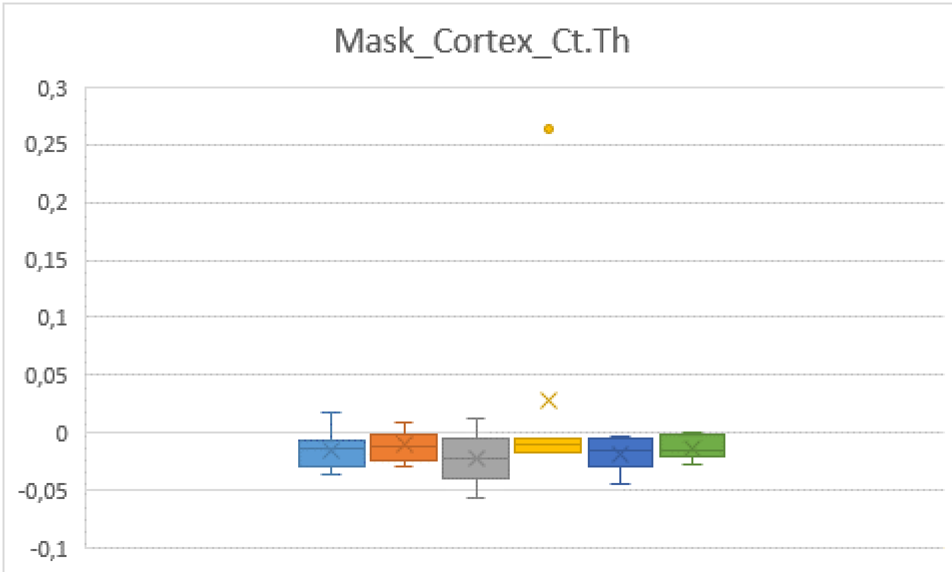

Manual_Upper_Endplate_TV
1,2
1
0,8
0,6
0,4
0,2
0

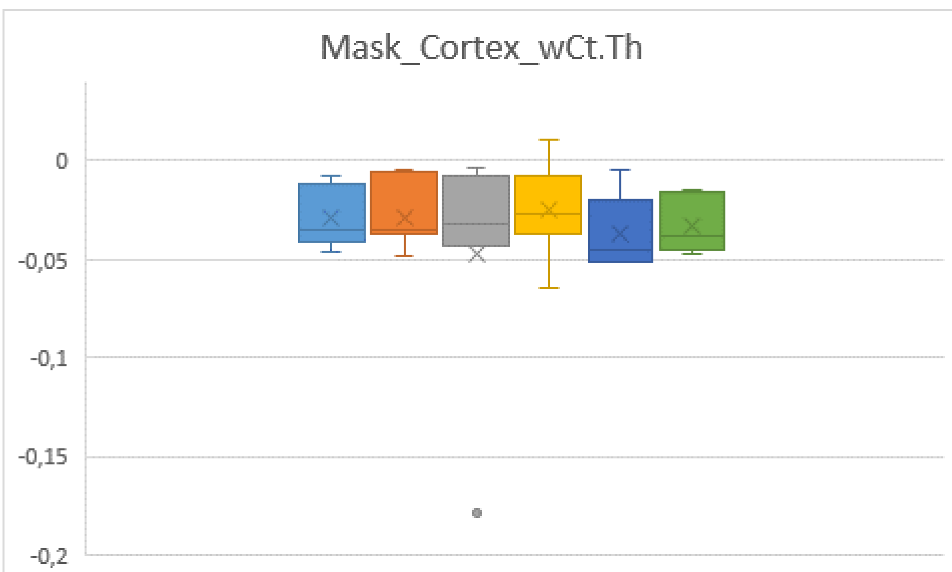

Mesh_Upper_Endplate_TV
1,6
1,4
1,2
1
0,8
0,6
0,4
0,2
0

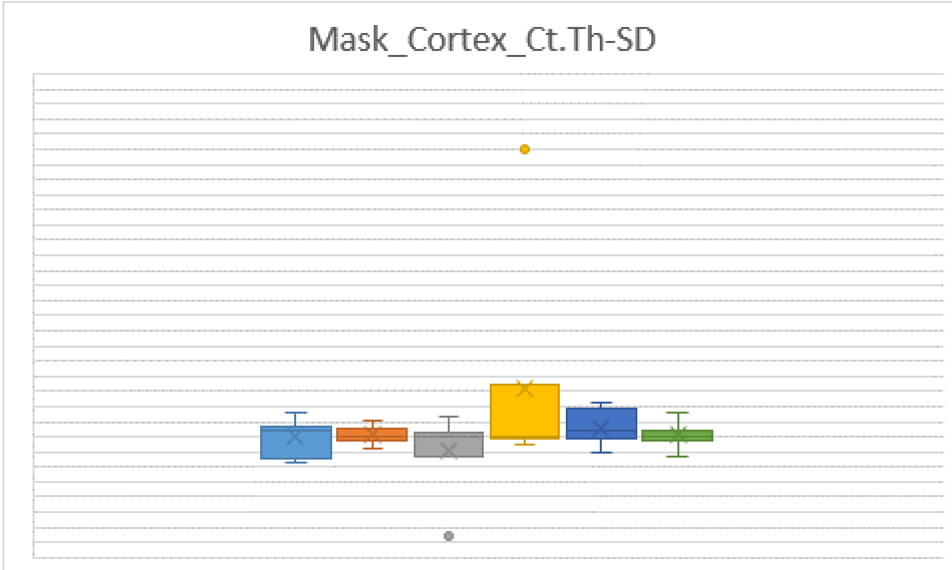

Manual_Upper_Endplate_BMD
60
40
20
0
-20
-40
-60
-80

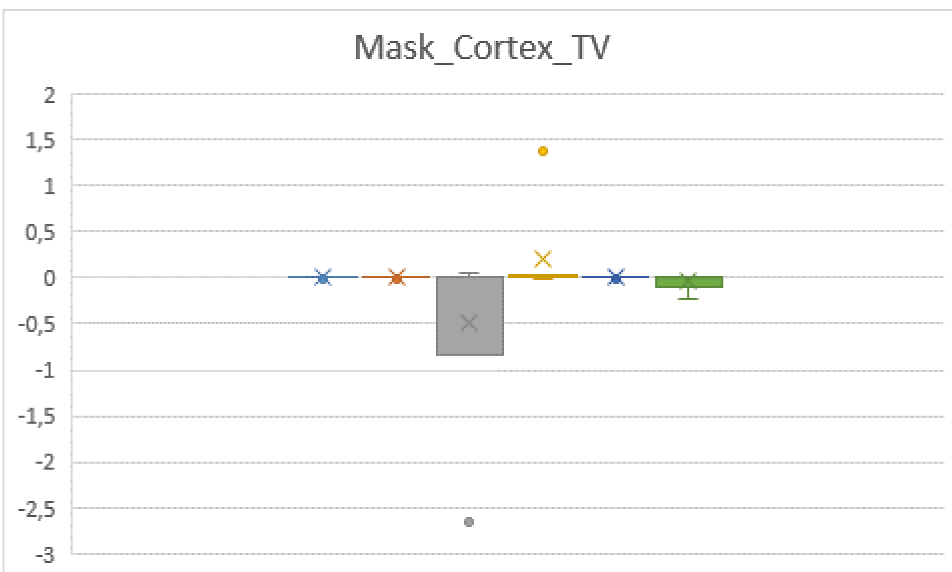

Mesh_Upper_Endplate_BMD
20
10
0
-10
-20
-30
-40
-50
-60

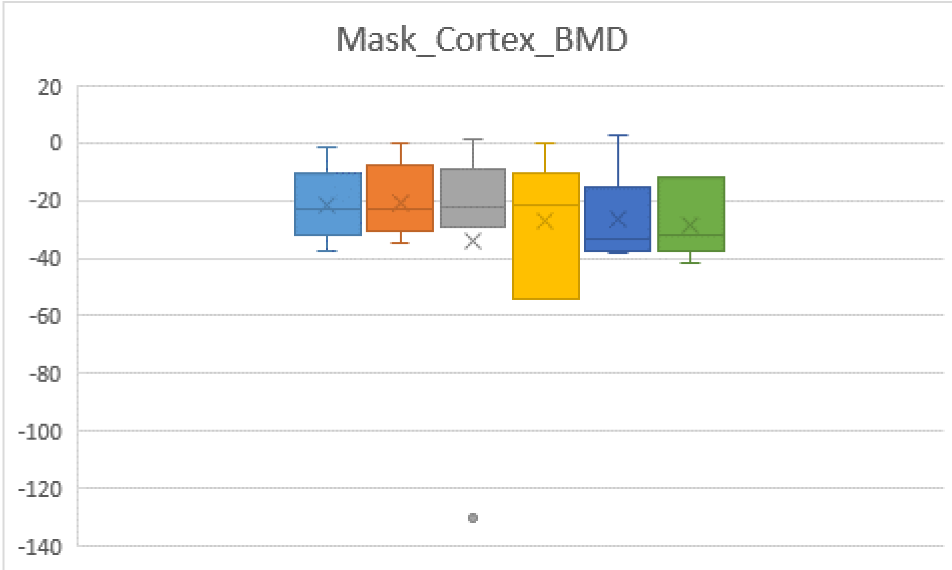
- **Box-Plots for Mask**
  - **Cortex:**



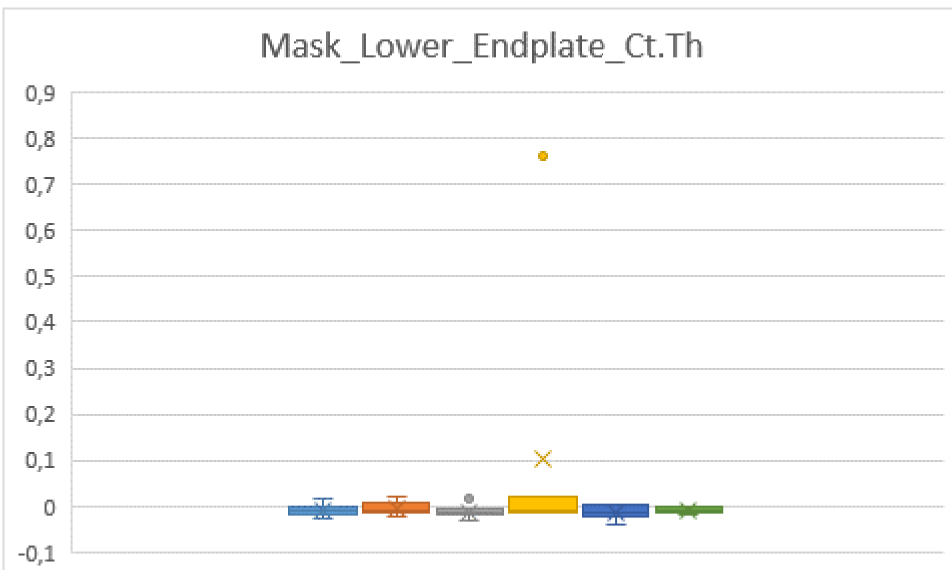


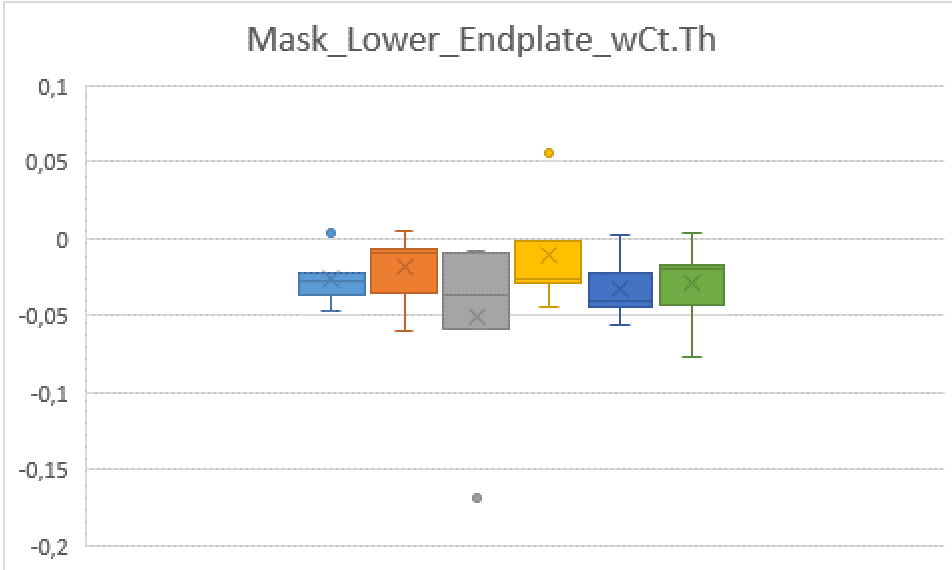

Mask_Cortex_Ct.Th-SD

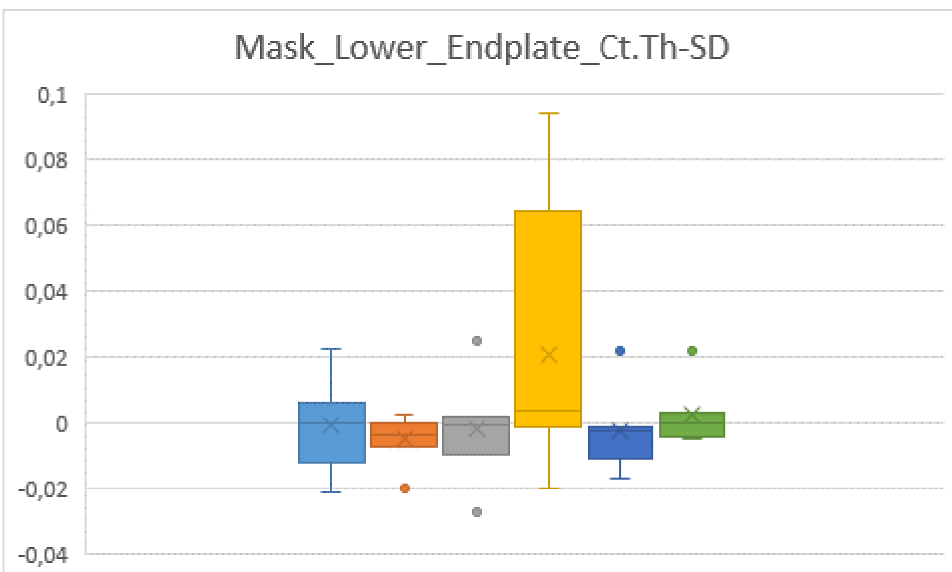

Mask_Cortex_TV
2
1,5
1
0,5
0
-0,5
-1
-1,5
-2
-2,5
-3

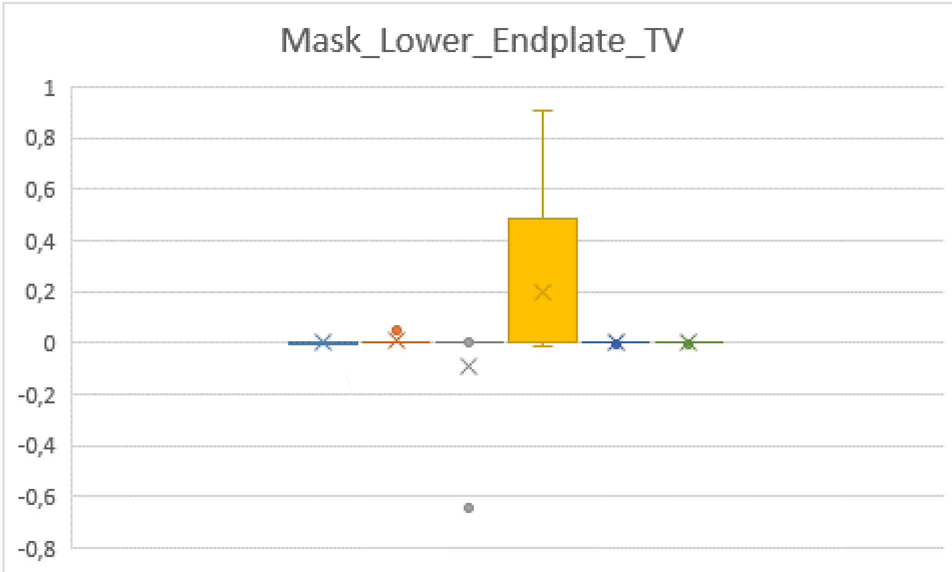


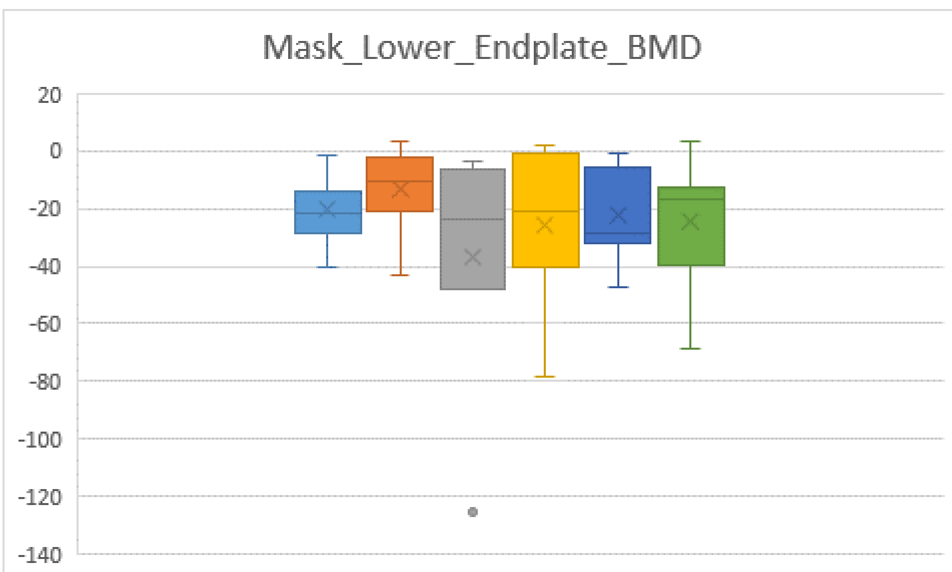
- **Lower_Endplate:**



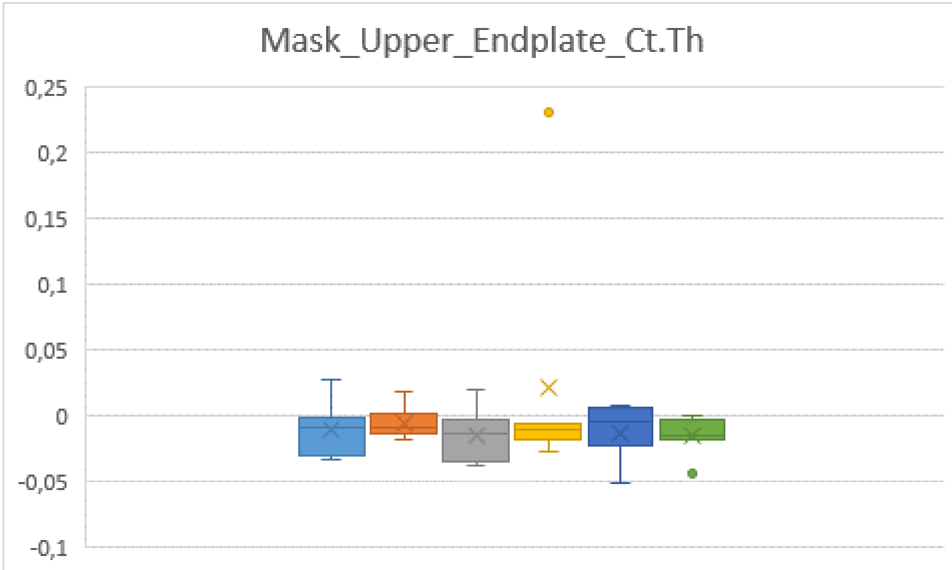

Mask_Lower_Endplate_wCt.Th
0,1
0,05
0
-0,05
-0,1
-0,15
-0,2

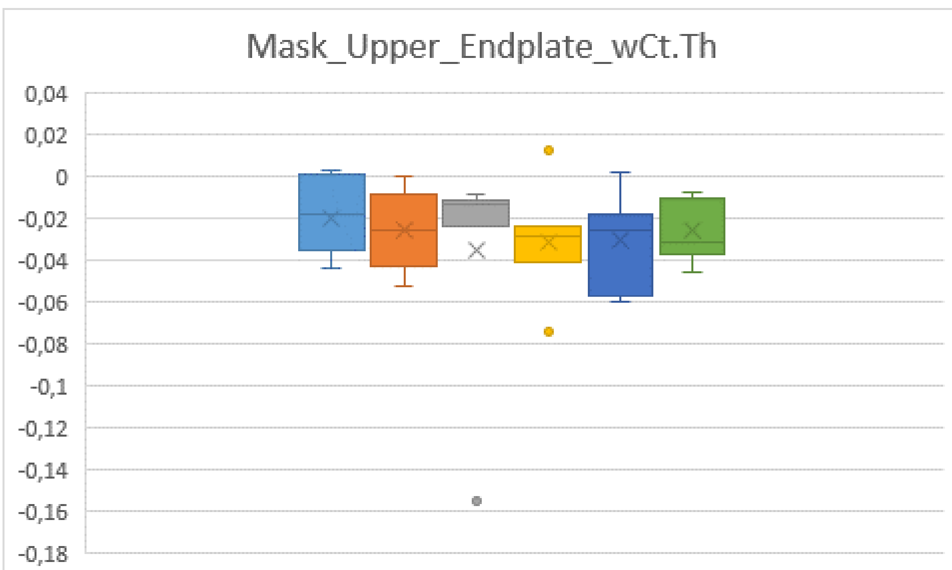

Mask_Lower_Endplate_Ct.Th-SD
0,1
0,08
0,06
0,04
0,02
0
-0,02
-0,04

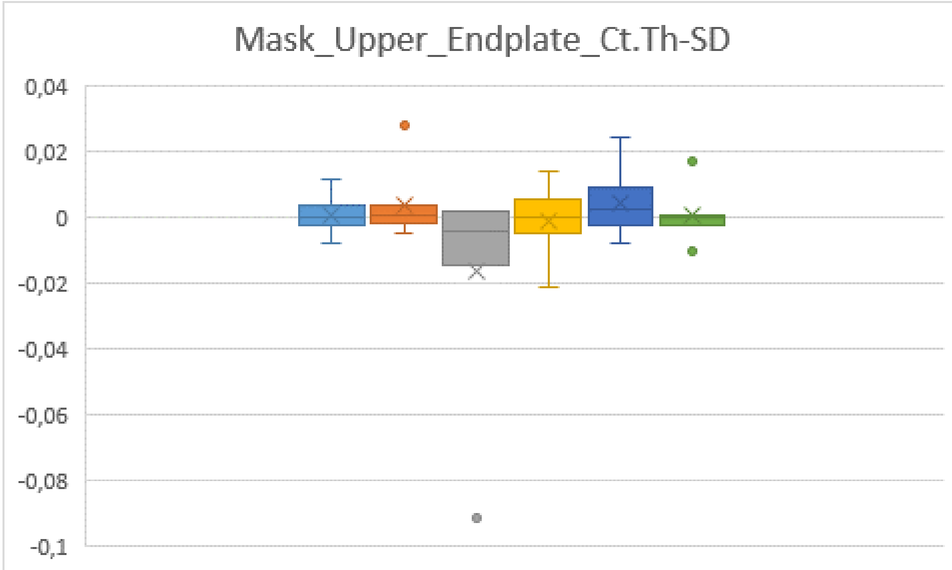

Mask_Lower_Endplate_TV
1
0,8
0,6
0,4
0,2
0
-0,2
-0,4
-0,6
-0,8

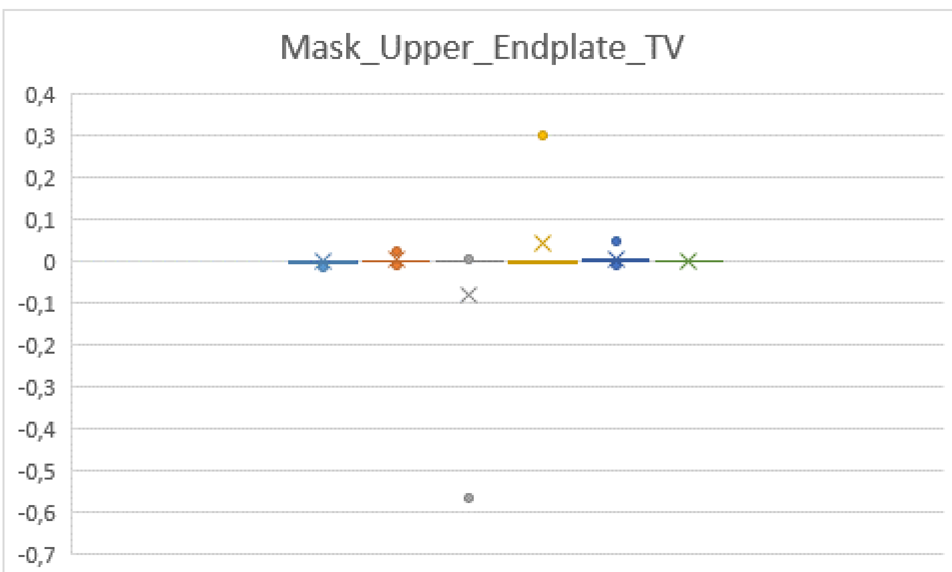

Mask_Lower_Endplate_BMD
20
0
-20
-40
-60
-80
-100
-120
-140

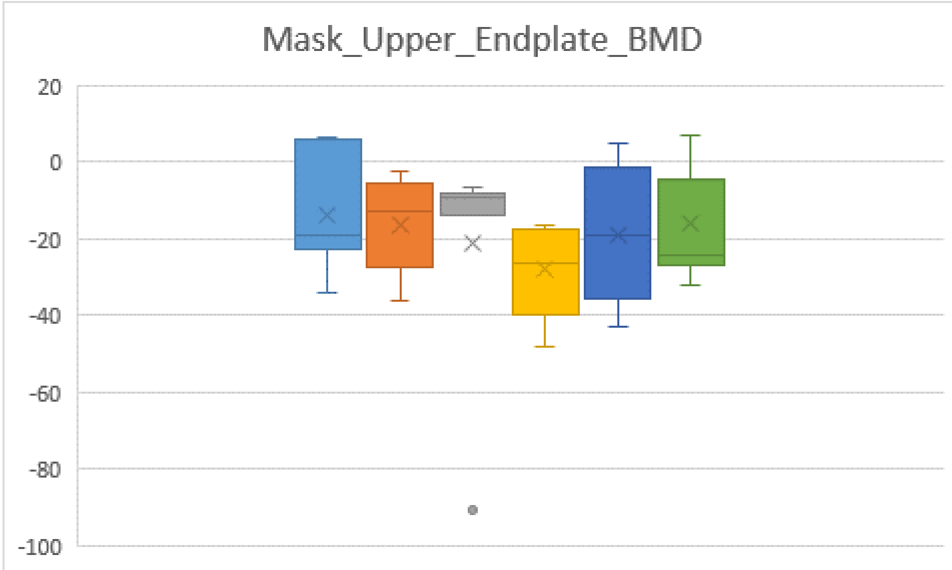
- **Upper_Endplate:**



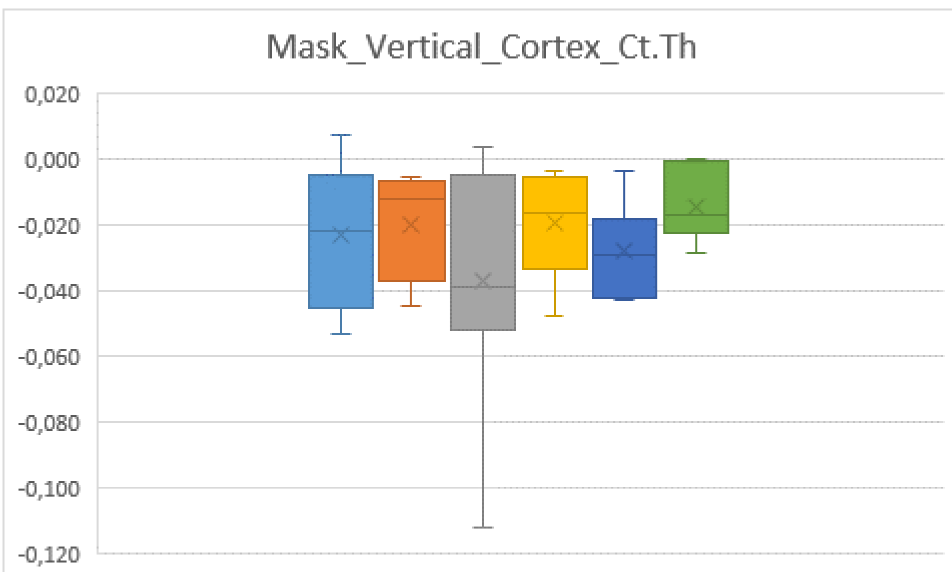


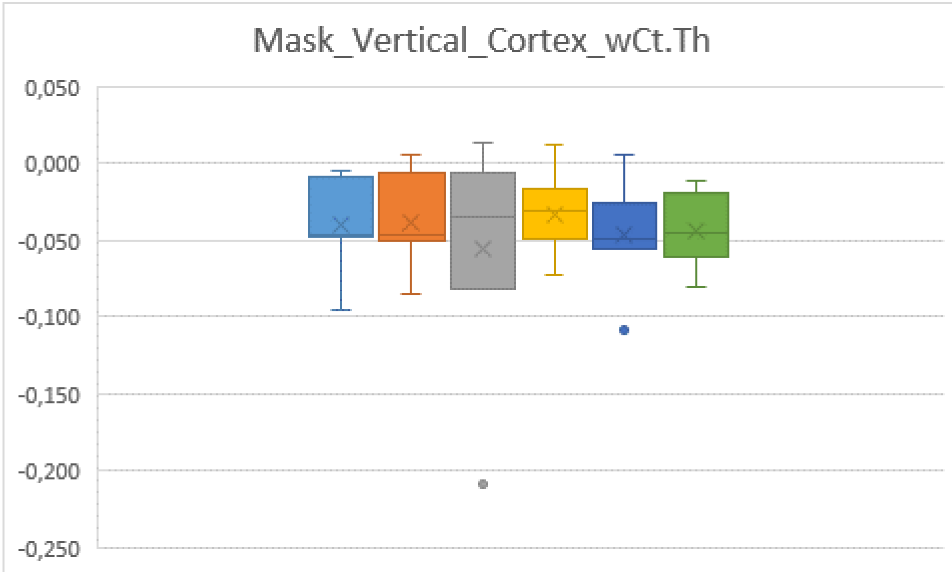

Mask_Upper_Endplate_Ct.Th-SD
0,04
0,02
0
-0,02
-0,04
-0,06
-0,08
-0,1

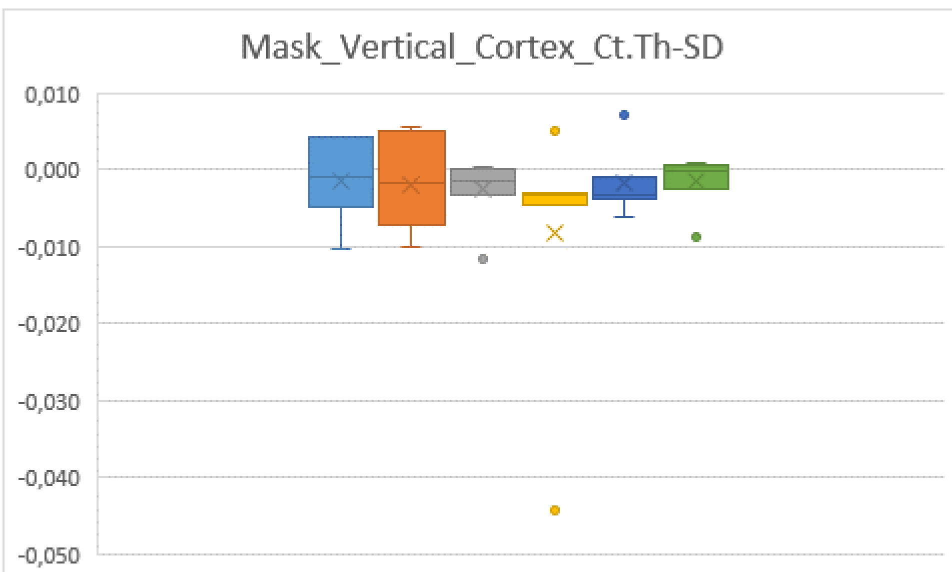

Mask_Upper_Endplate_TV
0,4
0,3
0,2
0,1
0
-0,1
-0,2
-0,3
-0,4
-0,5
-0,6
-0,7

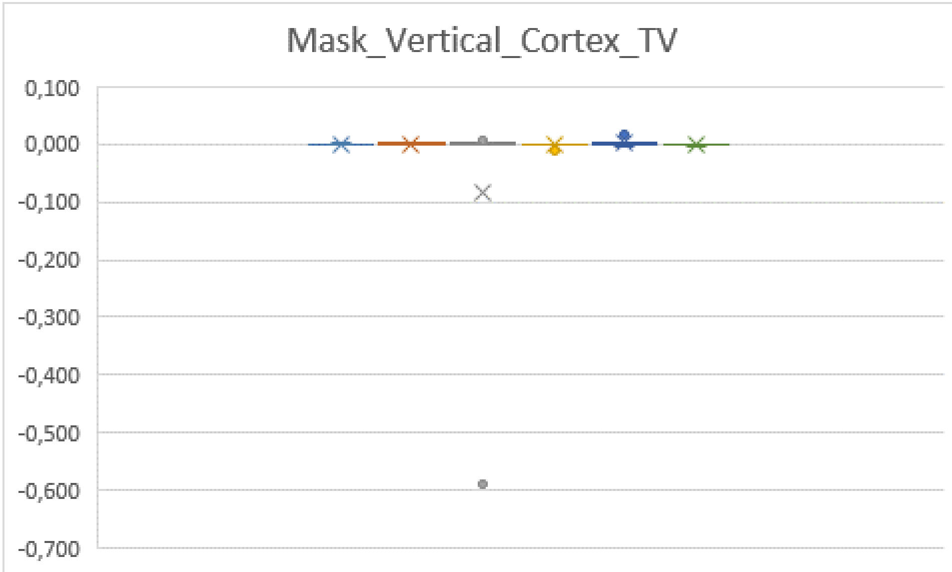


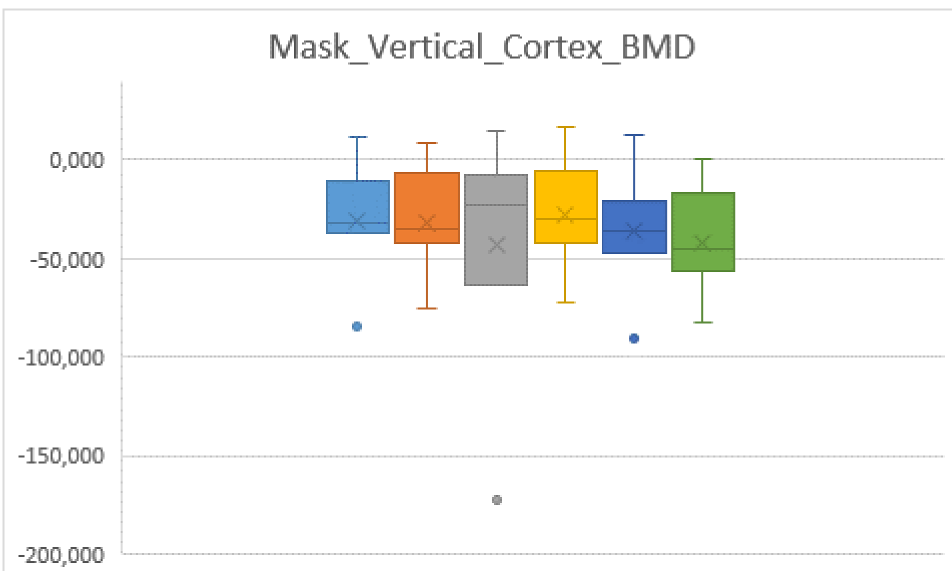
- **Vertical_Cortex:**




Mask_Vertical_Cortex_wCt.Th
0,050
0,000
-0,050
-0,100
-0,150
-0,200
-0,250


Mask_Vertical_Cortex_Ct.Th-SD
0,010
0,000
-0,010
-0,020
-0,030
-0,040
-0,050


Mask_Vertical_Cortex_TV
0,100
0,000
-0,100
-0,200
-0,300
-0,400
-0,500
-0,600
-0,700


Mask_Vertical_Cortex_BMD
0,000
-50,000
-100,000
-150,000
-200,000