DAAPMed: A Data-aware Anchor Point Selection Tool for Medical Models in VR Environments

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Abstract: There is a number of problems where the analysis of medical datasets requires the selection of anchoring points in 3D space, such as the measurement of anatomical structures (i.e. lengths of bones), pathological structures (i.e. tumors), and the measurement of other elements such as the air contents in the lungs or the gut. Previous research indicates that measurement tasks can be usually carried out more efficiently in VR environments than in desktop-based systems. However, there is a lack of tools for measurement support for medical models in VR environments. This paper presents a new VR-based interaction technique, Data-Aware Anchor Points for Medical models (DAAPMed), specially focused on the efficient selection of 3D points in datasets rendered using methods with semi-transparency such as Direct Volume Rendering. We will show that our method is effective, precise, and reduces the amount of movements required to set the anchor points as compared with other classical techniques based on clipping planes.

1 INTRODUCTION

In medical applications, the quantitative analysis of spatial relations between structures is crucial for many tasks such as diagnosis, treatment and surgical planning, and documentation. These measurements include, among others, the extension of pathological structures or the distance between pathological structures and structures at risk (blood vessels). In the field of Neurosurgery, for instance, distance between the brain surface and the ventricles is an important parameter that may determine the surgical trajectory. In a different field, digestologists are interested in performing a morpho-volumetric analysis of the amount of air in different organs such as the gut or the lungs, for diagnostic purposes. In order to carry out these quantitative analyses, researchers set several anchor points using medical images as a support (Accarino et al., 2009). However, the use of these 2D images does not facilitate the perception of the relative position of the structures, and as a consequence, it is often rough for accurately locating anchor points and thus obtaining precise 3D magnitudes.

Advances in volume visualization allow for the 3D reconstruction and analysis of anatomical structures from a stack of intensity-based images acquired from, usually, CT or MRI modalities. Initial algorithms identified and extracted the isosurfaces of the anatomical structures as triangle meshes. This process is time-consuming and loses contextual information. Later methods directly render the volume (Direct Volume Rendering, or DVR) by assigning color and opacity to the samples as a function of its density by using pre-defined transfer functions. Semi-transparencies provide a means to increase the amount of information visible to the users, and facilitate establishing spatial relationships between elements such as the skin and the bones. This led the development of new techniques for anchor point definition in desktop-based applications. However, occlusions still remain as a problem for the selection. This is often addressed with the introduction of clipping planes showing the volume cut mapped on them.

Reitinger *et al.* (Reitinger et al., 2006) found that measurement tasks can be carried out more efficiently in a Virtual Reality environment than in a desktop setup. The cost reduction of VR systems and GPUs is helping the introduction of such systems in surgical planning and diagnose. Stereo vision facilitates the perception of the relative position of anatomical structures, although occlusion remains as a research problem.

The purpose of this paper is to provide an easy-to-use tool for the fast and accurate selection of 3D points on the implicitly defined surfaces of anatomical structures present in a volume dataset in a virtual

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environment. It is important to note that we are not interested in selecting a concrete structure, but a point on it, without any previous surface extraction nor segmentation process. Additionally, the occlusion problem remains, as well as the fact that a VR selection environment is not familiar to medical experts.

The contributions of our paper are threefold:

- DAAPMed: An anchor point selection tool suitable for medical models in VR environments that enriches the selection ray trajectory with the information of candidate anchor points. These are automatically computed by performing an on-the-fly isosurface detection along the ray (see Figure 1).
- A series of visual cues that provide feedback on the ray position through the use of mirror views and supporting planes.
- A user study that analyzes the accuracy and performance of the selection, and compares with the classical selection using clipping planes.

The implementation of all these components (both GPU and CPU) guarantees real-time feedback and interaction. This is an important issue in VR environments which require rendering the model twice.

The user study showed that our technique is effective, with an accuracy compared to a selection tool in a desktop-based application with a mouse, and more efficient. Furthermore, it also reduces the efforts (hand displacements) and time required for the selection as compared with a classical clipping plane technique in a Virtual Reality environment.

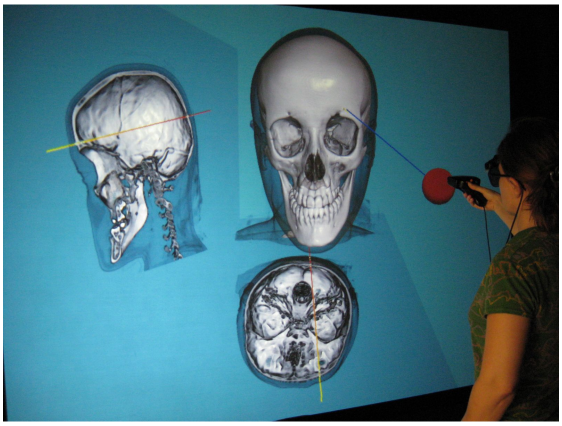

Figure 1: User interacting with a model using the DAAPMed metaphor.

2 RELATED WORK

In a pioneer work, Hinckley et al. (Hinckley et al., 1994a) proposed a 3D user interface for pre-operative neurosurgical planning based on the physical manipulation of familiar real-world objects (head, cutting-plane and stylus-shaped props) in free space to access and manipulate a virtual model. This approach offers the possibility of selecting anchor points in a brain model. They use a clipping plane to access occluded or interior points in the brain and then select anchor points on it as the intersection of the linear trajectory defined by the stylus and the cutting-plane. Qi and Martens (Qi and Martens, 2005) also focused in designing a 3D (tangible) user interface for the manipulation of a clipping plane into a volume dataset in a small size VR system (based on a 14” display), but their system does not provide any selection mechanism. More recently, Song *et al.* (Song et al., 2011) propose the use of a touch mobile for manipulating (positioning and orienting) a slicing plane. Since their objective is exploration, they do not address the problem we are concerned with: anchor point selection.

Preim *et al.* (Preim et al., 2002) introduced a set of applicable tools for the computation of distances, angles, and volumes in 3D visualizations. The tools are 3D virtual objects such as a distance line, a ruler and angular measurements that are manipulated using the mouse in a desktop-platform. They allow to determine anchor points on the surface of the pre-segmented anatomical structures. Rossling *et al.* (Rössling et al., 2010) proposed a method for the automatic determination of different distance−based measures (shortest distance, diameters and wall thickness) also on segmented anatomic structures. The necessity of this kind of tool is justified by the fact that manual distance calculation is tedious and imprecise in single 2D slices, and although it is possible to achieve an accurate result in 3D, it would also be tiresome. However, completely automatic measurements are difficult to generalize due to the great variety of problems and anatomical structures. Notice that both previous approaches (Preim et al., 2002; Rössling et al., 2010) work on triangle mesh representations, so a surface extraction process is needed previously to use them. Moreover, they always select the nearest visible point and they do not deal with semi-transparent models.

Reitinger *et al.* (Reitinger et al., 2006) presented a 3D measurement toolkit developed for liver surgery especially tailored for a VR platform. Their measurements include distance, volume, and angles. Their evaluation indicated that VR-based measurement tools have a sufficient benefit compared to 2D desktop-based systems in terms of task completion time. In terms of accuracy, slightly better results in most of the tasks were achieved. The anatomical structures models (liver, vessels,...) are computed through segmentation from CT scans and they are represented by opaque triangle meshes where the user may select points by using a virtual pencil. Hagerdorn *et al.* (Hagedorn et al., 2007) proposed a set of tools for performing measurements in a virtual reality visualization environment. A 3D Rubberbanding line for selecting *free* points in the scene is proposed. They use clipping planes for accessing interior parts of the volume dataset. Their scene is also composed by triangle meshes.

Segmentation and surface extraction are time consuming operations. To overcome this problem, Hastreiter *et al.* (Hastreiter et al., 1998) suggest direct volume rendering of the entire data volume, giving insights to interior and superimposed information. In order to inspect interior structures, independent clipping planes provide an intuitive way to virtually cut off parts of the volume data set. Then, anchor points can be interactively placed on the clipping planes. Gallo *et al.* (Gallo et al., 2008) present a Virtual Reality system for the exploration of volume datasets using a Wiimote. Apart from the basic interaction techniques for navigating they propose a mechanism of selection of points based on the classical ray-casting technique adding the mechanism of *fishing reel* in which the users can move the cursor closer or farther away by using two buttons in order to accurately locate a mark. Unfortunately, points'positions are not aware of the isosurfaces and no visual cue is used to reveal the cursor when it is moved into an occluded region.

Many researchers have investigated 3D object selection techniques for general -non medical- VR applications where the objects are represented by polygonal meshes; they focused on improving the user experience in this kind of tasks (Bowman et al., 2004). *Ray-based* techniques (Mine, 1995) have shown a better performance than *point-based* techniques. These former approaches are usually based on a cone or a ray. Since our interest is on accurate anchor point selection, we only consider ray-based tools. In order to solve the inherent problem of multiple intersection candidates, several disambiguation techniques have been proposed. Olwal *et al.* (Olwal and Feiner, 2003) describe the *flexible pointer*, a ray cursor technique that allows users to point around objects with a curved arrow, to select fully or partially obscured objects. It is important to note that most of these VR selection metaphors are focused on selection and manipulation of objects (not points) in populated scenarios, and thus they were not specially concerned about accuracy in point selection.

Grossman *et al.* (Grossman and Balakrishnan, 2006) explored 3D selection techniques for volumetric displays and proposed new ray cursor techniques which provide disambiguation mechanisms for multiple intersected targets. The *Depth Ray* tool augments the ray cursor with a depth marker. The position of this marker is changed dynamically moving the hand forwards and backwards. As the hand also controls the placement of the ray cursor, the two phases could potentially interfere with each other. To solve it, they propose the *Lock Ray*, a similar technique, where selection and disambiguation phases are carried out sequentially, in a two-step process. First the user selects the ray. Once it is locked, the depth marker appears. Then, forward and backward hand movements fix the depth marker and the intersected target closest to it is highlighted in red indicating that it can be selected by releasing the button.

Our approach also decouples the selection and disambiguation phases in two sequential steps (Grossman and Balakrishnan, 2006), though using a cycling method for candidate selection (Hinckley et al., 1994b). In contrast to these previous works, we work directly with the captured volume dataset (using DVR) without any kind of costly preprocess to extract the isosurfaces.

3 DAAPMED METAPHOR

Our objective is a user-friendly, efficient, accurate anchor point selection technique that facilitates getting measurements in VR environments with medical models. We also require ease of use and limiting the amount of effort the user has to perform. In contrast to normal desktop environment, where working with a mouse allows the user to rest the arm, in 3D environments the user usually does ample arm movements and has no surface to rest. With the objective of facilitating the integration with the specialists' clinical work, we directly use the captured volume dataset rendered using DVR with a transfer function that shows semi-transparent and opaque structures (see Figures 1 and 2).

As a first approach, we extended and adapted to 3D the classical desktop point selection using a clipping plane (see Figure 3). However, as shown in our user study, this metaphor requires quite a long time and large movements from the user, because the correct definition of a clipping plane suitable for posterior point selection is difficult. In order to overcome these limitations we have developed a ray-based approach that uses the data information to facilitate the ray setting and point selection, reducing time and displacements.

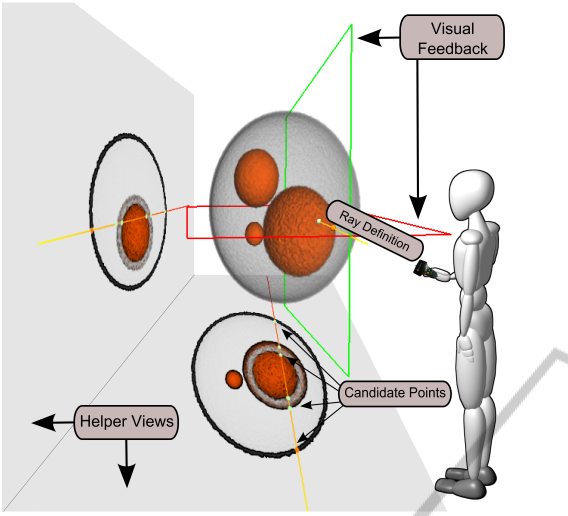

Figure 2: DAAPMed metaphor: A ray is used for selection, and a couple of supporting planes help the user to locate it in relation to the 3D structures. Potential anchor points, represented by colored small spheres, are computed as the intersections of the ray with the isosurfaces. Finally, Helper Views provide a better perception of the ray position as well as aids disocluding interior candidate points. Notice that the bottom view shows that the large orange sphere is hollow.

3.1 Data aware 3D Selection Metaphor

Studies have shown that ray-based selection techniques often result in faster selection times than hand extension techniques in VR environments (Bowman et al., 1999). Unfortunately, as commented previously, ray cursor techniques have an inherent problem: the ray may intersect multiple objects. A naïve approach simply selects the first target which is intersected; however, it becomes very difficult or even impossible to select occluded points. Thus a more sophisticated method is required. The DAAPMed metaphor has three main components (see Figure 2):

- Ray Cursor Tool. It casts a pointing ray through the volume. The ray path visualization is enriched with the candidate selection points and its supporting planes, which provide a better insight of its position and orientation.
- Helper Views. We provide two views that help to understand the position of the ray inside the volume. This extra-visualization is inspired by the Magic Mirrors View (König et al., 1999), but, instead of showing the whole model, our view shows the model clipped by a plane that enables the possibility of showing the ray trajectory without any occlusion.
- Disambiguation Mechanism. Once the ray is locked, we may select among the different intersections of the ray with the isosurfaces in the model. We adopt the same solution as Hinckley (Hinckley et al., 1994b) cycling from one target to the next.

The key difference with previous selection methods is the ability to work with volumetric models by automatically generating candidate points through a rapid isosurface detection. Moreover, we also add visual cues that facilitate the understanding of the ray position and orientation, and disocclude inner intersection points.

Figure 2 shows all the components involved in the metaphor. In this example, the dataset consists of four spheres of different materials. The metaphor works as follows: when the user presses the back button of the input device, the *selection task* starts and the ray is painted with a gradient color from red to yellow (in this way we provide users with a visual cue of the depth of the ray). Throughout this process, the system continuously computes the proper set of candidate points. This set is composed by all the intersections of the ray with the implicitly defined isosurfaces. Upon button release, the last ray shown is locked, meaning that the selection phase has finished and the disambiguation task begins. The nearest candidate point is marked in orange (default selection) and the rest of the points are in white. The joystick provided by the input device allows the user to cycle between all the candidate points. This is convenient because it reduces movements. Since candidate points may have a random distribution, tracking the user's movement to reach all the candidate points without a large arm movement (as proposed in (Grossman and Balakrishnan, 2006)) would be difficult and might result in large varying patterns for different rays of the same volume.

As the 3D ray is painted over the volume, it is sometimes difficult to interpret how the volume is traversed. In order to give the user a second cue on the intersection of the ray with the volume, we provide the Helper Views. These showed to be of great utility, since some candidate points are usually occluded by other parts of the volume (Figure 1 shows a snapshot of our technique and the accompanied video details the interaction process). We augment the visualization of the volume models with a wireframe representation of the cutting planes used in the Helper Views in order to provide the users with a visual feedback of the placement of such planes.

3.2 Implementation Details

In this section we give some details on how the isosurfaces are detected in real time as well as on how the

Helper Views are created. One key difference with other anchor point selection methods is the automatic detection of isosurfaces on-the-fly along the pointing ray. Since we have a non-segmented model, this isosurfaces must be determined in real-time, as they depend on the transfer function. Throughout all the process we use a DVR method using a GPU-based ray casting.

3.2.1 Ray - Isosurface Intersection Detection

Volumetric models can be seen as a 3D scalar function $f : V \subseteq \Re^3 \rightarrow \Re$ (e.g. density value of a material). Let $TF : \Re \rightarrow \Re^4$ be the transfer function used in the volume rendering algorithm, that assigns color and opacity to a scalar property. First of all, we have to define the conditions that a point p of the volume dataset V must fulfill to be considered a boundary-surface candidate point. These are:

1. p must belong to a visible material. This condition can be expressed formally as $opacity(TF(f(p))) > 0.0$
2. p must belong to the boundary of a well-defined isosurface. This condition is satisfied if:
   (a) The gradient at point p, $\nabla f(p)$, has to be well defined. This means that $\|\nabla f(p)\|$ is larger than a certain threshold. This threshold is automatically set by a previous analysis of the range of the magnitudes of the gradient.
   (b) There exists a change in the sign of the direction of the gradient at p at the neighborhood of p. This property expresses the fact that the boundary passes through p.

Since the detection of the boundary condition ($2.b$) may not be real-time in a VR environment, the information necessary to test this condition is precomputed. This is carried out by applying a 3D edge detection process (Monga et al., 1990) to the volume V and storing the result in a 3D texture which consists of a value per voxel that indicates the possibility of being crossed by the boundary of a surface. The second condition is tested by checking whether p belongs to a boundary voxel. Our system guarantees testing at least a point for each voxel intersected by the ray, thus the accuracy of our approach is related to voxel's size. As shown in Section 4, we obtain an accuracy comparable to that of both a clipping plane selection approach and to a desktop application which works with a triangle mesh models (not a volume model) for the anatomical structures. This is due to the fact that surface extraction methods also have an accuracy proportional to the voxel size. Its computation is comparable to the model loading time.

3.2.2 Helper Views

The goal of Helper Views is to provide additional information on the exact position of the ray inside the volume. These views are drawn on two fixed planes, located to the left (YZ) and bottom (XZ) of the volume dataset (see Figure 2). Images displayed on these image planes are generated with the same algorithm used for rendering the volume dataset but clipping it by the plane that contains the ray and is the most parallel to each of the image planes YZ and XZ, respectively. This has a main advantage: it shows the candidate points that lie inside the volume, therefore facilitating ray selection without previous manipulation of the volume (i. e. clipping).

These views can also be adjusted by the user: they can be rotated, moved, and the image projected onto them may be zoomed. We provide a default orientation with the planes slightly oriented towards the viewer and at a relatively small distance from the object that seems usable for several models. This default orientation has been decided after a previous informal experiment with users that did not participate in the user study. To facilitate its manipulation, the projection onto the Helper View plane is stored in a texture; therefore, the different operations on these views come at no cost. Figure 2 shows the placement and the visualization of the Helper Views design. The visualization of the cut volume dataset is enhanced with an illustrative motif:view-dependent contours computed by using a Sobel kernel in order to enhance the silhouette of the clipped region.

4 EVALUATION AND RESULTS

We have conducted a formal user study to evaluate

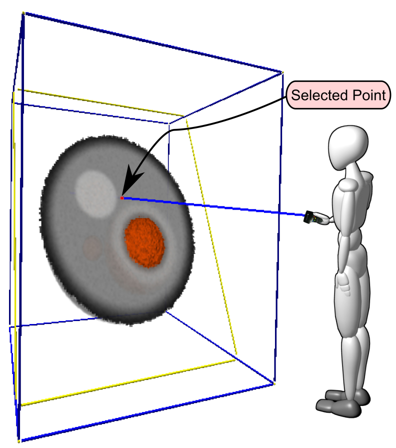

Figure 3: Adaptation to VR of the clipping plane technique for selecting points located on it.

the accuracy, efficiency and ease of use of our approach. We take as a reference an implementation of the Clipping Plane (CP) selection method, since it is a technique that has been widely used in medical applications (see Section 4.1 for the details of our implementation). Furthermore, we have also compared the precision of our technique with a typical desktop application based on triangle meshes (see Section 4.3). The results show that our technique is as accurate as a desktop-based method and exhibits good timings. We also found that the users required far less movement with our system than with CP.

We performed the user study in an immersive virtual reality setup composed of a 2.7×2 meters passive stereo PowerWall. Users were tracked using an Intersense IS-900 Motion Tracking System device consisting on a Head Tracker and a MiniTrax Wanda with a joystick and five programmable buttons.

4.1 Design Details of the Clipping Plane Technique in Virtual Reality

In order to compare our selection technique with the classical approach for anchor point selection using clipping planes (CP), we ported this metaphor the following way. Two buttons of the input device allows the user to set the action to be performed: rotate or translate the clipping plane. While the user is pressing the selected button, the clipping plane is rotated or translated accordingly to the user's hand movement. The rotation is based in the paradigm of the *Rolling Ball* (Hanson, 1992). The translation is always done in the direction of the plane's normal. Once the plane is fixed, the user can select a point on it using the ray-cursor paradigm. By pressing another button, the user indicates the desired point, so every point inside the volume, belonging to the plane, could be a candidate point to be selected. However, due to changes in the holding forces done by users when pressing or releasing a button, called Heisenberg effect (Bowman et al., 2002), the accuracy of the selection may be affected. In order to solve this problem, we enhanced the visualization of the ray with a freezing timer.

4.2 Test 1: Synthetic Points

Medical doctors often address two different point selection problems: selection of well-established anatomical points and distance measurement. As a consequence, we decided to test two different tasks: one regarding the selection of some specific points and the other focused on performing the calculation of certain measure.

In this first test, the points and distances shown to he users are synthetic in the sense that they do not belong to relevant anatomical points common in medical environments. In Section 4.3 we will address a case more related to practical medicine.

In these experiments, we want to evaluate the efficiency and the accuracy of our proposal with respect the CP technique. Throughout the tests, we measured several magnitudes that will provide information on the amount of displacement (and thus, effort) each technique requires. We recorded the following indicators for each of the experiments in the test:

- Task Completion Time. We measured the amount of time devoted to complete each experiment.
- Input Device Footprint. We measured the length of the total path followed by the device to complete each task.
- User Footprint. It measures the user displacement inside the VR environment.
- Accuracy: This value measures the error in the selection with respect to the reference points, taking into account the dimension of the voxel dataset as a metric of the error made.
- Hit Rate. This variable tracks the number of hits the user has to do. Since each introduced point may be changed if it is not satisfactory, we also count the number of times a point is selected before its validation.

Data Preparation. We prepared two different datasets. The first one was used for training, while the other was used for the test. The training model consisted of a set of four spheres of different material (see Figure 4-left). The second model consisted of a typical model in volume visualization, a CT tooth dataset using a transfer function that enhanced the outside and inner shape of it (see Figure 4-right).

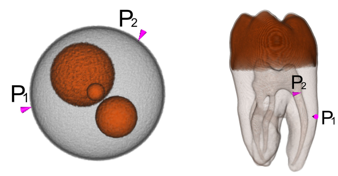

Figure 4: The training (left) and testing (right) datasets. The figures show the anchor points to be selected in the first experiment.

Subjects and Procedure. 17 subjects participated in the evaluation; 13 male and 4 female, ranging between 23 and 63 years old. Subjects were asked to classify (as Low, Medium or High) their experience in a VR setup, experience with input devices and expertise in 3D application. All of the participants were

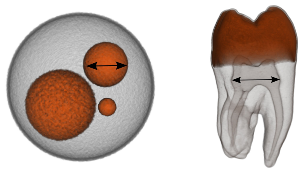

Figure 5: Images that show the second experiment description, as presented to the participants in the test.

people from our department. Computer scientists at different levels of studies (master and PhD students) and faculty staff.

Every user performed both experiments once. Before the first experiment started, a complete training (using the spheres dataset) was performed to get familiar with the two interaction techniques to evaluate: DAAPMed and CP techniques. The test was divided into two blocks, one for each technique. The order of the blocks was chosen randomly in order to avoid skewing one of the techniques with a learning effect.

As said before, the test consisted of two kind of experiments: selecting two predefined points, and measuring a certain magnitude defined by two points. For the first experiment, we asked the users to introduce two anchor points (P_1 and P_2) at positions that were marked in the model with the use of a cone representation (see Figure 4). Once completed, we stop tracking the movements of the user until she is ready for the next experiment. The second experiment consisted of taking a measure (calculated as a distance between two anchor points). We refer to this calculation as *Thickness*. The specification of this experiment was accompanied with different descriptions and pictures of the goal (see Figure 5). None of the users involved in the experiment had any problem understanding the objective of the experiment. Users can repeat the selection of a point as many times they need. But once the point was validated by the user, he or she could not repeat its placement.

4.2.1 Results

A repeated measures within subjects design was used. The independent variable was the technique and the dependent variables were the set of tracked variables. A one-way analysis of variance (ANOVA) comparing both techniques was use.

Table 1 summarizes the statistical analysis of the relevant variables. For each variable the mean and the standard deviation are shown. The first experiment is tagged as P_1 and P_2, corresponding to the two anchor points. Second experiment is tagged as *Thickness*.

Regarding *Completion Time*, there is significant evidence in all the experiments that DAAPMed performed better than CP. For P_1 ($p = 0.028$, $F = 5.83$), for P_2 ($p = 0.008$, $F = 9.35$) and for *Thickness* ($p = 0.044$, $F = 4.79$). Figure 6 shows the total time for each technique.

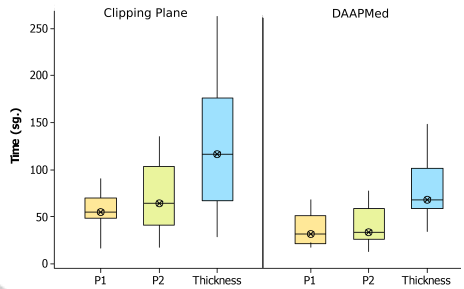

Figure 6: Results of the completion task timings. The boxes show the interquartile range with the median as the horizontal bar. The whiskers extend to the minimum and maximum of the data. CP exhibits longer selection times.

Regarding *Input Device Footprint*, we measured the length of the total path which the device took to complete the experiment. We have found a significant effect on the *Input Device Footprint* variable for P_1 ($p = 0.036$, $F = 5.24$) and for P_2 ($p = 0.004$, $F = 11.70$). Figure 7 illustrates the effect. The reduction of footprint is especially important since a handheld 6-DOF device is being used, which can lead to fatigue with extended use (Ware and Slipp, 1991).

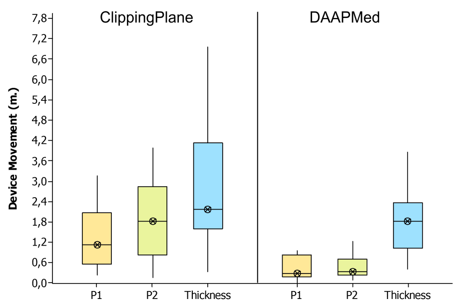

Figure 7: Input device footprints. The boxes show the interquartile range with the median as the horizontal bar. The whiskers extend to the minimum and maximum of the data. For point selection it is clear that DAAPMed method performed significantly better than CP.

We also split the movement done by the device taking into account whether the movement was due to an exploration phase (rotating or translating the model) or due to the selection phase. We have only found significative statistical difference between the two techniques for P_2 ($p = 0.007$, $F = 9.44$), for the rest of the experiments DAAPMed performed better comparing means and standard deviations. With CP technique, the user performs similar amount of moves during navigation and during selection. On

Table 1: The overall statistical results of the evaluation shown as means and standard deviations of the variables measured for the tooth model. Regarding the mean and the standard deviation, DAAPMed is superior to CP. The one-way ANOVA analysis showed which differences were statistically significative.

	CP			DAAPMed		
	P_1	P_2	Thickness	P_1	P_2	Thickness
Accuracy	0.76 ± 0.23	0.93 ± 1.37	1.15 ± 0.81	0.562 ± 0.229	1.37 ± 3.13	1.081 ± 0.79
Completion Time	62.42 ± 34.08	73.8 ± 47.1	119.8 ± 65.5	43.07 ± 36.54	41.1 ± 25.7	84.1 ± 43.4
Movement Tool	3.711 ± 2.75	4.86 ± 4.81	7.92 ± 5.57	2.335 ± 3.26	1.88 ± 1.46	5.42 ± 3.31
Movement User	1.942 ± 1.53	2.41 ± 2.33	4.281 ± 3.23	1.331 ± 1.87	1.261 ± 1.04	2.835 ± 1.79

the other hand, when selecting using DAAPMed technique, users devoted a larger effort to the navigation phase than to the selection one (see Figure 8).

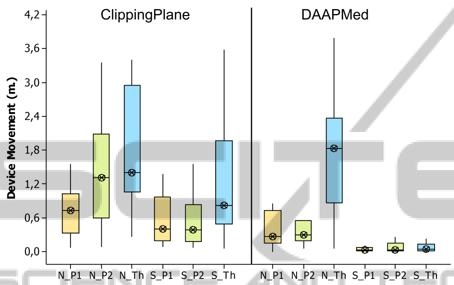

Figure 8: Input device footprints. The displacement carried out by the device is split in two states: navigation (N_$\{P_1, P_2, Th\}$) and selection (S_$\{P_1, P_2, Th\}$).The boxes show the interquartile range with the median as the horizontal bar. The whiskers extend to the minimum and maximum of the data.

We also measured the movement carried out by the user. In all cases, our system requires a lower amount of movement by the user. The analysis shows that the movement done in DAPPMed is significantly less than CP for P_2 ($p = 0.009$, $F = 8.72$) and for *Thickness* ($p = 0.03$, $F = 5.62$).

Thus, we can conclude that our system behaves better than CP.

Concerning the accuracy, the mean values show better performance for our technique. However, we did not find significant statistical differences. The reason could be that with CP technique you can get enough precision if you know exactly the point you have to select. In order to do a deeper analysis, we perform another test which is closer to a real medical scenario since we use points with anatomical significance.

We have also tracked another set of variables, such as the number of points selected before validating them, or the number of exploration versus selection phases, but we could not extract any behavior or pattern from those.

4.3 Test 2: Anatomic-based Points

We have carried out a second experiment where the workflow is closer to a real medical environment. The selection points are points with specific anatomic meaning commonly used to place anchor points or measuring distances. The objectives of this test were twofold: a) Testing if our VR application was as accurate than the desktop application and, b) finding whether DAAPMed technique was more accurate than the CP technique.

To carry out this analysis we use a specific desktop-based application for the morpho-analysis of the abdominal air (Accarino et al., 2009). In this application, users had to mark a set of points on the skeleton of a model in order to infer some measures. Using this application, we marked the set of points shown in Figure 9. The exact location of these points were saved to a file in order to evaluate the accuracy reached in a VR setup. Users, with the helping of the image shown in Figure 9, have to locate these points as accurately as possible.

Data Preparation. The model used was taken from a medical dataset. It has a resolution of $512 \times 512 \times 369$ and a voxel dimension of $2.042^2 \times 3.56$mm. The desktop-application uses a mesh representation of the data extracted from the volume dataset using the Marching Cubes algorithm. Our application uses the same volume model visualized with a DVR algorithm.

Subjects and Procedure. 13 subjects participated in this test: 10 male and 3 female, ranging between 23

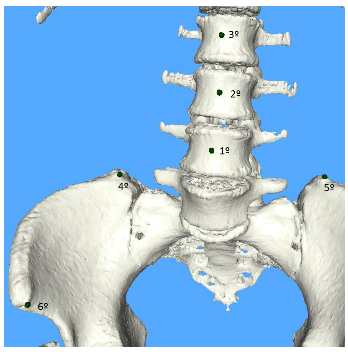

Figure 9: Model used in the second test. This test confirms that DAAPMed is as accurate as a clinical environment in a desktop-based computer and more accurate than the CP technique.

and 40.

In this experiment we proceed in the same way as the first test. Each participant performs the test once. Before the experiment, users were provided with a short (1-3 min.) training session. The test was divided into two blocks, one for each technique: CP and DAAPMed. The order of the blocks was chosen randomly in order not to introduce some learning effect.

4.3.1 Results

The results are summarized in Table 2. The first and second rows show the mean and the standard deviation for both techniques. The third and fourth rows show the statistical significance information (p anf F). For all the points introduced (except P_4 and P_5), the DAAPMed technique shows significant statistical difference with respect CP. We do not have a clear idea on the lack of significance of points P_4 and P_5, but it might be that the specification of their corresponding positions was not as clear as with the others. Figure 10 shows a boxplot for all the tasks performed.

We also compared the accuracy with the desktop approach and obtained errors that did not differ significantly, which demonstrates that we may achieve comparable results in a VR environment. In both cases, the error performed was below the voxel size.

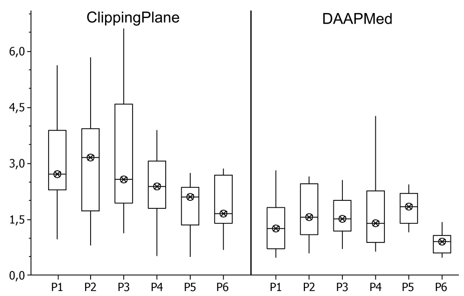

Figure 10: Accuracy by technique. The boxes show the interquartile range with the median as the horizontal bar. The whiskers extend to the minimum and maximum of the data.

4.4 Post-questionnaire Results

To complete the information, we also asked the subjects to fill some questionnaires, to know the preferences of the users between the two techniques. All responses in the post-questionnaire were measured on a Likert scale of 1-5, where 1 meant the worst value and 5 was the best value. The results are shown in Figure 11. The answers seem to indicate that DAAPMed metaphor is more suitable than the CP technique.

The users noted two major problems with respect

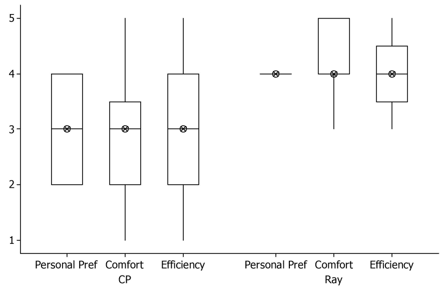

Figure 11: Results obtained from a personal preference evaluation questionnaire. These results show that the users' perceptions are quite positive with our tool.

to our technique. The first one is the inherent jittering of the tracker, that made selection affect user performance. Only two users agreed in that it seems to produce a more relevant effect to the ray-based selection than to the plane-based. Furthermore, in all the experiments, the ray-based approach showed a better behavior than the clipping-planes system. The second issue was the lack of ray refinement: most users suggested that a fine tuning of the ray, after its initial positioning would be welcome. We let this work for future improvements.

5 CONCLUSIONS AND FUTURE WORK

We have presented a new interaction technique for selecting points in a volume dataset. This selection technique follows the *ray casting* paradigm, enhanced with an automatic calculation of the set of suitable points of interest by an on-the-fly determination of the isosurfaces along the ray path. The feedback with the interaction is enhanced with a meaningful visualization called *Helper Views* that provides context for the ray selection and shows occluded detected candidate points that would be otherwise invisible to the user without posterior and ad-hoc volume manipulation.

The user study showed that our technique is easy to learn and to use. Despite the limited precision of the 3D input devices, our technique achieves a precise 3D interaction thanks to the automatic anchor point calculation provided by the system. Users felt more comfortable and achieved better results with our system than with the clipping plane technique.

In the future we would like to continue working on the improvement of the accuracy with the current, imprecise devices, and we also want to carry out a study of the overall system with medical experts.

Table 2: The overall statistical results of the evaluation shown as means and standard deviations of the tolerance error. We can clearly see how the DAPPMed metaphor provides better results for all the tasks than the CP method.

	P_1	P_2	P_3	P_4	P_5	P_6
CP	2.944 ± 1.305	3.018 ± 1.495	3.171 ± 1.729	2.336 ± 0.879	2.066 ± 1.095	2.070 ± 1.169
DAAPMed	1.293 ± 0.671	1.701 ± 0.703	1.605 ± 0.501	1.766 ± 0.570	1.789 ± 0.424	0.280 ± 0.078
p,F	0.002 - 16.55	0.011 - 9.01	0.005 - 11.58	0.187 - 1.96	0.385 - 0.81	0.001 - 17.42

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