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Distance and Force Visualisations for Aneurysm Clipping Simulations

Master Thesis

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Abstract

In the field of unruptured cerebral aneurysms, clipping is less and less often the method of choice. The few aneurysms that have to be treated by clipping are usually complex cases. The resulting lack of practical experience in combination with complex cases is a huge problem, from which the need for more training possibilities arises. Therefore, a few approaches dealing with clipping simulations for aneurysms were developed. Within the scope of this master thesis, a clipping simulation was developed to establish concepts for visualising additional information. These concepts were then evaluated regarding their added value and applicability. The additional information include distance visualisations and tractive force visualisations. The distance visualisations aim to enhance spatial relations, improving the navigation of the clip, whereas the tractive force visualisations display the force acting on the vessel surface by the applied clip. This is relevant because a high tractive force can lead to vessel injuries during the surgery.

The developed visualisation concepts include colour maps and visualisations based on rays, single objects and glyphs. These concepts were evaluated by practising doctors and medical students via an online survey. Additionally, one neurosurgeon evaluated individual parts during and at the end of the development. The overall evaluation revealed that regarding tractive force visualisations the colour map is the most appropriate concept, providing the most added value. The need for distance feedback was not recognizable in videos presented in the survey, but the qualitative evaluation with one neurosurgeon demonstrated the benefit. Here, the distance rays outstripped the other concepts. Besides the added value and additional support of these two visualisations in an aneurysm clipping simulation, they may also be applicable in other, similar simulations or serve as a basis for developing further visualisations.

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1 Introduction

In this introductory chapter the topic of simulating the treatment of unruptured cerebral aneurysms by clipping will be presented. First the general motivation to include additional information in a clipping simulation tool is explained. In the medical relevance section (1.2) the possible treatments of cerebral aneurysms are described, including the relevance of an aneurysm clipping simulation. The next section serves to outline the scientific relevance of visualising both types of information, the distance and tractive force. The development was promoted by cooperating with a medical expert. The expert was Dr. med. B. Neyazi, a neurosurgeon at the university hospital Magdeburg. Whenever there is the talk of a neurosurgeon serving as a contact person and informant, Dr. med. B. Neyazi is meant.

1.1 Motivation

Within this master thesis a clipping simulation tool for unruptured cerebral aneurysms was developed. Since treating unruptured cerebral aneurysms by clipping is on the decline and the few cases treated by clipping are usually complex cases, such a tool is a good way to counteract the lack of practical experience and exercise of neurosurgeons and medical trainees.

Apart from the clipping process, the main focus is on providing additional information. The user should be provided with distance information so they are aware of the distance between the clip and vessels while interacting with the clip. By adding this information, the user should be supported in finding an optimal way to the aneurysm, be made aware of distances and get a better feeling for dimensions and spatial relations. Additionally, tractive force visualisations showing the tractive force on the aneurysm and the surrounding vessel wall were developed. This information is supposed to help the user to detect the optimal placement of clips to keep stress on the parent vessel as small as possible. Unfortunate placement that applies too much stress on the vessels can lead to injuries. With the help of the tool, the different concepts of representing the distance information and tractive force will be evaluated. The evaluation reveals whether or to what extent the specific concepts are helpful and supportive.

1.2 Medical Background Information for Intracranial Aneurysm Clipping

So-called unruptured cerebral or intracranial unruptured aneurysms are bulgings of blood vessels at the Circle of Willis which is a circle of arteries in the brain. Cerebral aneurysms

have a prevalence of about 3% [1]. Most aneurysms are asymptomatic and thus diagnosed by accident during imaging for another affliction [2]. The main danger of cerebral aneurysms is rupture, resulting in a critical subarachnoid hemorrhage, which is a subtype of stroke [3]. Because of the severe consequences of a rupture, the risks of not treating the aneurysms have to be compared with the risks of treatment [2]. Treating can be done by two main methods: surgical clipping and endovascular embolization [4]. Both methods aim to prevent the blood from flowing into the aneurysm.

As clipping is an open surgery, the neurosurgeon first has to perform a craniotomy [5], which is illustrated in Figure 1.1.

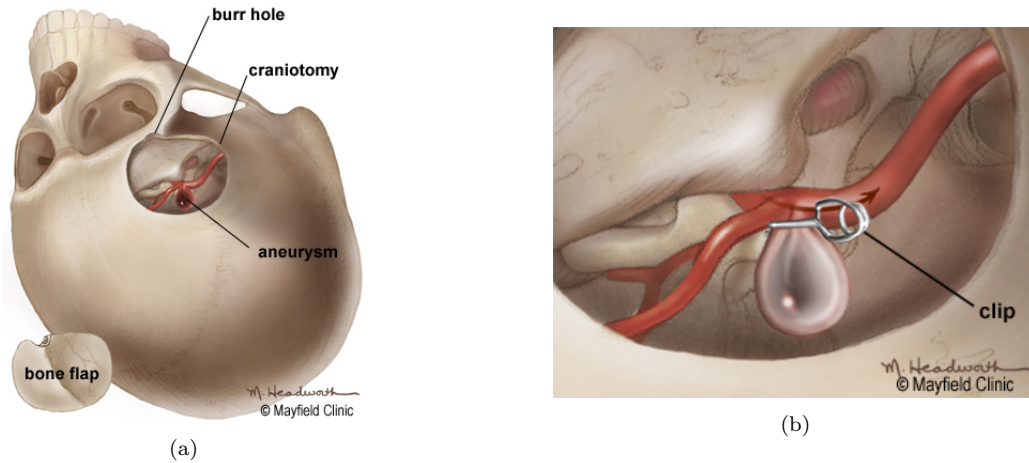


Figure 1.1: Procedure of surgical clipping. After opening the skull (a), the clip is placed on the aneurysm neck (b) [6].

After removing a part of the skull, the underlying dura mater is opened [5]. To open the subsequent Sylvian fissure and thus exposing the aneurysm, retractors may be used to form a corridor [5, 7, 6]. The process of carefully dissecting and exposing the aneurysm is shown in a real case in Figure 1.2. Then clips can be placed carefully on the exposed aneurysm neck, sealing off the aneurysm from its parent vessel [7, 6]. This procedure is shown in Figure 1.1.

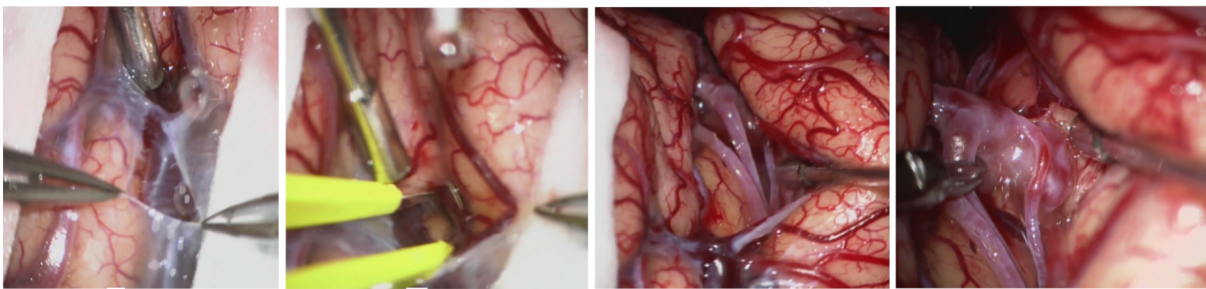


Figure 1.2: Procedure of dissecting the Sylvian fissure and exposing a small MCA aneurysm [8].

Common complications during this treatment are intraoperative rupture of the aneurysm and parent vessel injury both of which can be caused by the placement of the clip. Therefore, surgeons should place the clip parallel to the parent vessel's centerline [9, 10], limiting stress on the vessel wall [10]. Nevertheless, there are many more factors like anatomic properties and the existence of atherosclerosis influencing the choice of the clipping method [11, 12, 13]. So with the help of a computer-based simulation tool, surgeons

and trainees can try different methods and use the tractive force feedback to evaluate them. In clinical practice, this is not possible.

During a preliminary talk with the neurosurgeon, the necessity of this feedback was explained. He explained that during a clipping surgery the clip is carefully moved to the aneurysm, partially closed, opened and moved again and so on. This serves to find an optimal way of placing the clip by seeing but also feeling whether there is too much stress on the vessels. In a clipping simulation, this haptic feedback of stress is not available and it would be helpful to replace this by an appropriate visualisation.

In contrast to clipping, endovascular embolization is a minimally invasive procedure. Here, the aneurysm is reached via a catheter and different devices can be inserted, which can be seen in Figure 1.3. These can be for example spiral shaped platinum coils (Figure 1.3 (a)). Additionally, an inflated balloon can be helpful to guide the coils into the aneurysm. In case of aneurysms with a wide neck, a stent holding the coils in place is required (Figure 1.3 (b)). Besides coils, there are other devices like flow-diversion stents (Figure 1.3 (c)) or intrasaccular flow disruptors (Figure 1.3 (d)) [6]. A flow-diversion stent is a stent consisting of structural wires and a set of radiopaque wires woven together in a flexible braid, which is then placed in the parent vessel, preventing the blood from flowing into the aneurysm [14]. Intrasaccular flow disruptors, like Woven EndoBridge devices, are positioned inside the aneurysm sac, leading to an intra-aneurysmal thrombosis [15]. All mentioned methods can be seen in Figure 1.3.

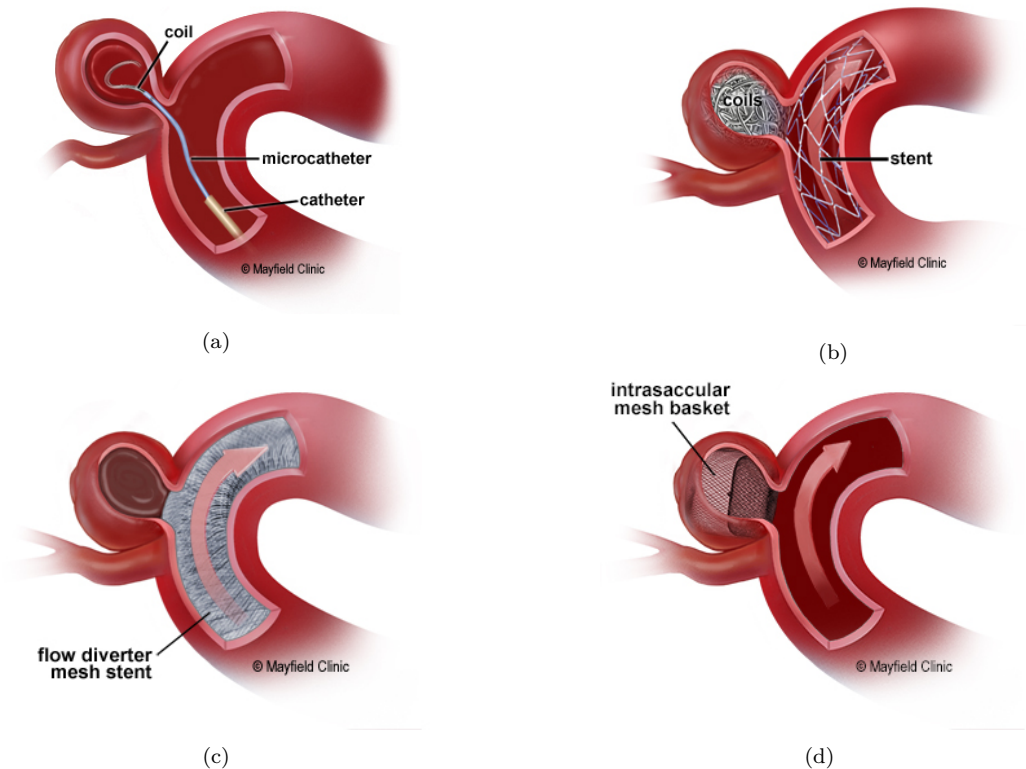


Figure 1.3: During endovascular embolization, the aneurysm is reached via a catheter. Through this, coils can be placed inside the aneurysm sac (a). If necessary, the coils can be held in place by a stent placed in the parent vessel (b). Alternatively, a flow-diverter consisting of a close mesh can be placed into the parent vessel (c). The last option is an intrasaccular flow disruptor, also consisting of a tightly woven mesh (d) [6].

The treatment of unruptured cerebral aneurysms has changed over the last few years. Lin et al. [16] investigated the treatment of ruptured and unruptured cerebral aneurysms in the USA from 1998 to 2007. As Figure 1.4 shows, the majority of unruptured aneurysms in the USA are now treated with endovascular coiling.

In a study by McDouals et al. [17] the temporal trends in cerebral aneurysm treatment were examined by investigating 4899 treatments of unruptured cerebral aneurysms in the years from 2006 to 2011. In total, 1388 aneurysms were treated by clipping and 3551 by coiling, revealing that the treatment of clipping is on the decline, whereas the treatment of coiling increases permanently.

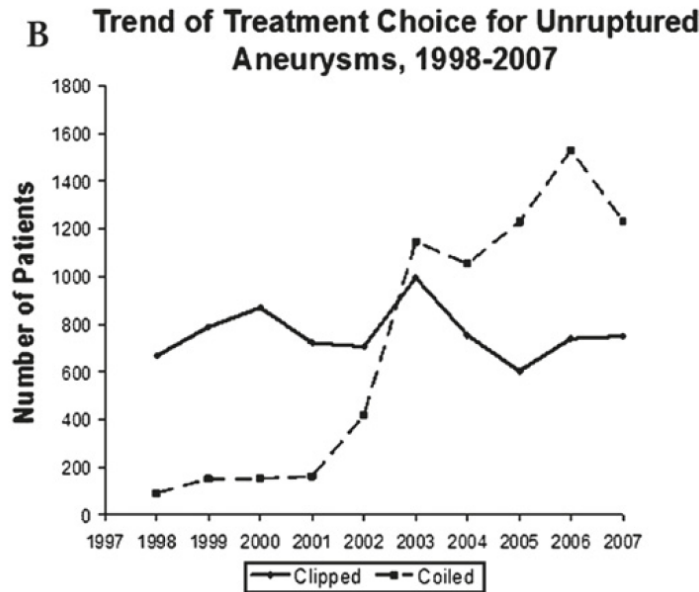


Figure 1.4: Trends of treating unruptured cerebral aneurysms by clipping and coiling [16].

Although the preferred method is endovascular coiling, there are still some cases where no coiling can be performed due to them being technically difficult [18]. Technically difficult and relatively uncommon cases are for example aneurysms that are too small or large for coiling, or other cases that require relatively much surgical time or a high number of clips [18]. Consequently, the small number of treating aneurysms by clipping and their complexity brings along the need for effective training to practice clipping [19]. To provide appropriate training, simulation tools for neurosurgeons and trainees are necessary, which is the motivation of this work.

1.3 Importance of Distance and Tractive Force Information for a Virtual Clipping Simulation

There are already a few approaches in the area of clipping simulations that will be presented and compared in Section 2. The aim of this work was to develop a simulation tool for applying clips with focus on visualising additional information. As additional information distance information and tractive force information were chosen. What exactly is meant by these information and why they are relevant is explained in the following.

Distance Feedback Computer-based systems are often implemented as desktop applications, where the interaction is completely different compared to the clipping procedure in a real surgery. One difficulty is interacting in a virtual three-dimensional(3D)-environment, rendered on a two-dimensional(2D)-display. Generally, so-called depth cues contribute to the humans' ability to see three-dimensionally. Visual depth cues can be divided into the two categories binocular and monocular depth cues [20]. Binocular cues for example are used for stereoscopic displays or virtual reality devices, where the eyes receive two slightly different images [21]. When using a monoscopic display as output device, which is the case in this work, these binocular cues cannot be used. Monocular depth cues are 2D information from which humans can partially reconstruct three-dimensionality [22]. These include for example occlusion, relative size and shadows [22], which can be used in 3D-applications, rendered on a 2D-display. Another depth cue is the texture gradient, which means that the texture of surfaces and for example the ground is scaled based on their distance and the underlying shape. In Figure 1.5, the effect of the texture gradient of the ground can be seen. In the left image the ground is inclined backwards, whereas the plane of the right image is vertical [23]. As in a surgery the vessels are not lying on a texturised surface, this cue is not present in the simulation.

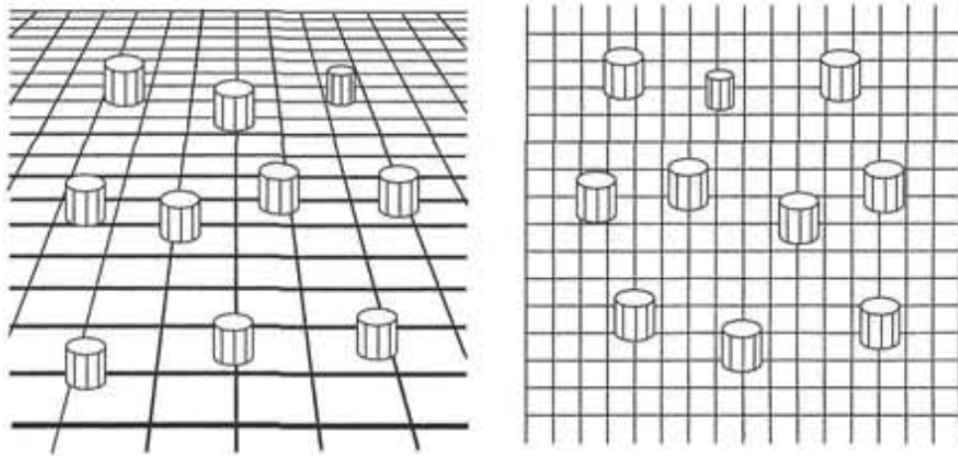


Figure 1.5: Impact of texture gradient. Left image showing a plane inclined backwards, whereas the right image shows a vertical plane [23].

The lack of several depth cues in such a context leads to more difficult interaction and navigation. Due to this, one part of this work will be the development of different methods of distance feedback and to evaluate whether they improve interaction and navigation within the clipping simulation.

Tractive Force Feedback Whenever a soft body is squeezed it results in a deformation of the corresponding object. One of the forces acting on the body and its surface is the tractive force, pulling it in the direction of the point of origin.

As mentioned in Section 1.2, possible complications during clipping are injuries of the parent vessel. These can occur if the tractive force on the vessel surface is too strong [9, 10]. As the tractive force is applied by the clip, the clip placement plays an important role. Therefore, it is crucial to include tractive force visualisations in such a clipping simulation. This way, the physicians have the possibility to assess different clipping methods considering the force applied on the vessels.

There are different approaches, detailed in the next chapter, dealing with visualising forces on the vessel and aneurysm surface. But as they deal for example with wall shear stress, they are mostly based on blood flow simulations. Consequently, they do not depict force applied by the clip but by blood. Furthermore, these approaches are not integrated in the environment of a clipping simulation tool. That is why this work presents and evaluates several concepts to visualise this tractive force and the usefulness in such a tool.

2 State of the Art and Derived Concepts

In this section, the related work and the derived concepts are presented. This is done by presenting the state of the art in the field of aneurysm clipping simulations. Afterwards, approaches and derived concepts of distance and tractive force visualisations are revealed. The next two topics are physic-based and deal with the deformation of soft bodies and collision detection which is important for a realistic simulation of navigating and applying clips. In the next section, the selection of appropriate aneurysm and clip models is discussed. Based on these fundamental individual components, the tool as a whole is presented with its graphical user interface and possible interactions. Conclusively, the requirements that the tool and the visualisations have to meet, are demonstrated and explained.

2.1 Aneurysm Clipping Simulation

To provide surgeons and trainees with additional training, several simulation tools have been developed in the last years [24, 25, 26, 27, 28]. Whereas Mashiko et al. [26] created a physical hollow elastic model, Alaraj et al. [24], Gmeiner et al. [25], Shono et al. [27] and Vite et al. [28] developed virtual simulations. In the following, all four virtual approaches are summarized, whereby all of them, except the one presented by Vite et al. [28], are patient-specific approaches.

Alaraj et al. [24] introduced a virtual reality simulation tool for clipping. This tool comprises an interactive stereoscopic immersive environment with the patient's imaging data and several tools, like clips and clip applier. After reconstructing a stereoscopic 3D model the user can select an appropriate clip. While moving the clip, the user is provided with haptic feedback by the haptic device Geomagic Touch (3D Systems Corporation, <https://de.3dsystems.com/haptics-devices/touch>, Rock Hill, South Carolina). With the help of this tool Alaraj et al. [24] aimed to evaluate the usefulness of a aneurysm clipping simulator as an education tool. One challenge several participants mentioned was grasping, opening and closing the clip because they were unfamiliar with the depth perception. The haptic feedback was perceived as realistic only by twelve percent of the participants. However, more than two-thirds of the participants mentioned that the simulation would help defining the approach to access the aneurysm safely.

Another virtual reality clipping simulator presented by Shono et al.'s [27] focuses on "tissue-dependent, modifiable, interactive, real-time deformation of the cerebral tissue complex" [27]. They divided the tool into two subsections, one for dissection and one for clipping. During the dissection phase, the user dissects the virtual arachnoid membrane and trabecula with a virtual microscissor. In the clipping phase, multiple clips are

available that can be moved and applied to a deformable aneurysm model. Both phases can be seen in Figure 2.1. For their implementation they used Unity (unity Technologies, <https://unity.com/de>, San Francisco U.S.) and made use of the PhysX engine NVIDIA for the elastic deformation.

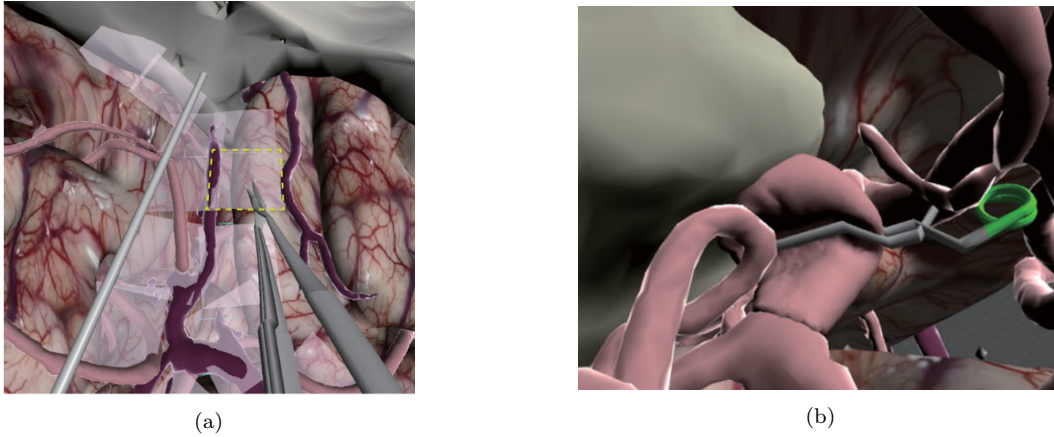


Figure 2.1: Two phases of clipping simulator: Simulated image of clip application (a) and cutting the virtual arachnoid membrane and trabecula (image before cutting) (b) [27].

For interacting with the simulation tool of Vite et al. [28], two haptic devices are used, one for manipulating a tool to separate the two lobes of the brain and the other for placing the clip. Like the previous approach, they also used a deformation based on the finite element method for tissue deformation. In contrast to the previous approaches they also included the opening of the Sylvian fissure with the help of an idealised brain model, which can be seen in Figure 2.2. During opening the Sylvian fissure and applying the clip, the surgical area is restricted by the cranial opening, defined by a neurosurgeon. As mentioned above, Vite et al. [28] did not develop a patient-specific tool, but used two reconstructed models of real patients. Additionally, they modelled several different instruments according to manufacturer's specification sheets.

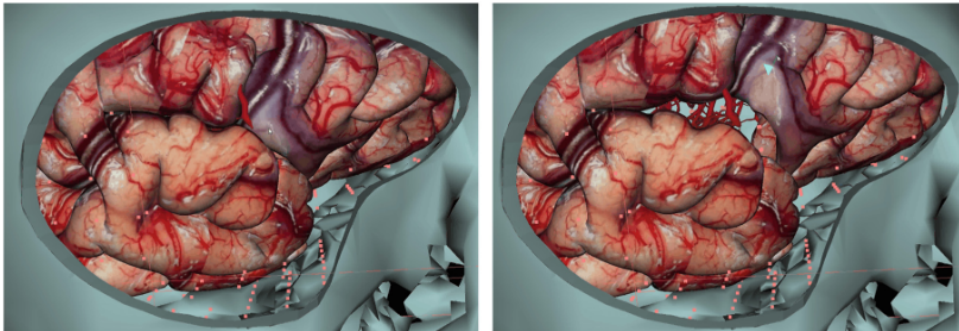


Figure 2.2: The simulated deformation of soft-tissue deformation of the brain through the Sylvian fissure at closed and opened states [28].

Gmeiner et al. [25] aimed to develop a virtual clipping simulator comprising haptic force feedback and real-time deformation of the vessel and aneurysm. For the deformation they used a finite element method discretizing the elasticity equations of continuum mechanics. Therefore, they made the assumption of a simplified isotropic linear material model, which disregards the layered structure, nonlinearity, and anisotropy of real arteries. After

clipping, the procedure is evaluated with a scoring system based on blood flow simulation. Figure 2.3 shows the evaluation mode of the simulation in comparison to real-life microsurgical images. The evaluation of the simulator was conducted by eighteen neurosurgeons. Although the clipping procedure itself was rated as adequate and acceptable, only one third of participants evaluated haptic feedback provided by two Geomagic haptic input devices as truly satisfactory.

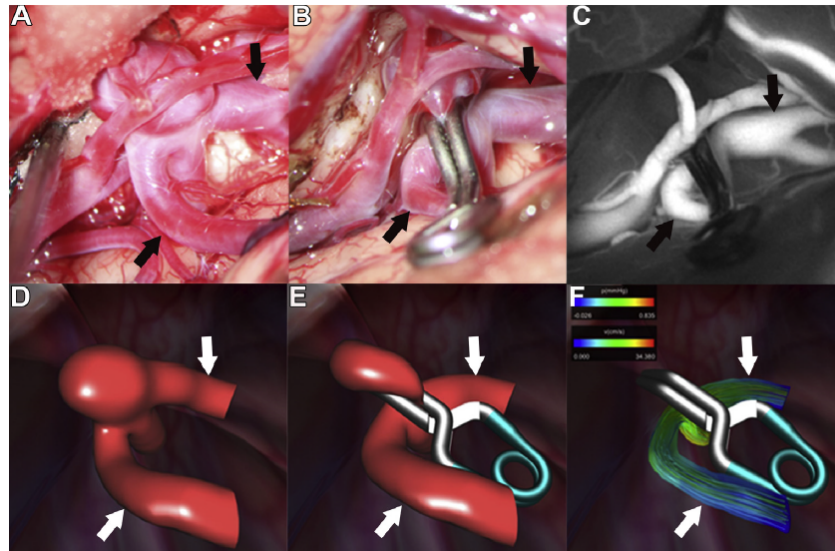


Figure 2.3: A, B: Real-life microsurgical clipping. C: Intraoperative angiography. D, E: Virtual clipping based on computed tomography angiography of the same patient. F: Virtual blood flow simulation in the evaluation mode [25].

The presented approaches can be divided into patient-specific and non-patient-specific approaches. Since the aim of this work is to develop and provide a tool for training and not for pre-operative planning, it was decided that it is more important to include different and representative cases instead of patient-specific data. The specific cases are presented in Section 2.5.

As all approaches aim to develop tools that are as realistic as possible, they intended to create realistic interactions by providing haptic feedback. They have in common, that the users were not satisfied with the haptic feedback. One important task of haptic feedback is knowing when the executor is touching something, otherwise it would be difficult to know when the clip is touching the aneurysm or a vessel.

In contrast to the other approaches, this work does not aim to provide a tool that is as realistic as possible, but to provide other or additional feedback.

2.2 Visualisations

To provide additional information, different visualisation concepts derived from related work are used. The related work and resulting concepts regarding force and distance visualisations are presented in the following subsections. Furthermore, the choice of an adequate colour scale is motivated.

2.2.1 Distance Feedback

As mentioned above, the haptic feedback provided in the presented approaches is rated as not appropriate. To support the users with other and additional feedback revealing the clip location and spatial relations, one type of additional information is distance information.

Distance feedback is not realistic in terms of being actually available during microsurgical clipping, but it can help preparing for such a procedure or help trainees to get a better feeling and understanding. Furthermore, the visualisation should facilitate the navigation of the clip in the simulation tool. As mentioned in Section 1.3, a 3D application that is displayed on a 2D screen provides only few depth cues. Consequently, distance visualisations counteracting this lack of depth cues and thus supporting the perception of spatial relations should be developed.

Visualisations related to aneurysms are mostly used to either show the blood flow [29] or other hemodynamic information like wall-shear stress [30]. On the other hand there are several approaches in the medical simulation field, for which displaying distance, usually between a tool and target anatomy, is relevant. Kersten-Oertel et al. [31] summarized different ways of visualising distances. One possibility is to display the distance numerically like Soler et al. [32] and Giraldez et al. [33], or showing it numerically in a bar graph like Kawamata et al. [34] did. Another common way is to use a colour-coding scheme, lighting up the specific anatomy, which can be seen in Katić et al.'s [35] approach. Colour-coded distance fields displayed on an anatomical structure are often used as an approach [36, 37]. Alternatively, Hansen et al. [38] proposes a distance-encoding silhouette instead of distance-encoding surface. Another possibility is to use additional geometric structures like Trevisan et al.'s [39] colour-changing dynamic sphere. Dick et al. [37] proposed two different distance visualisations for interactive pre-operative implant planning that were compared to just a colour-coded distance visualisation on the implant surface. They introduced a glyph-based visualisation, where colour-coded cylindrical glyphs orthogonal to the implant surface depict distances. This approach was compared to a slice-based visualisation with colour-coded distances displayed on the implant surface and additional slices bridging the volume between implant and bone. Both approaches can be seen in Figure 2.4 below.

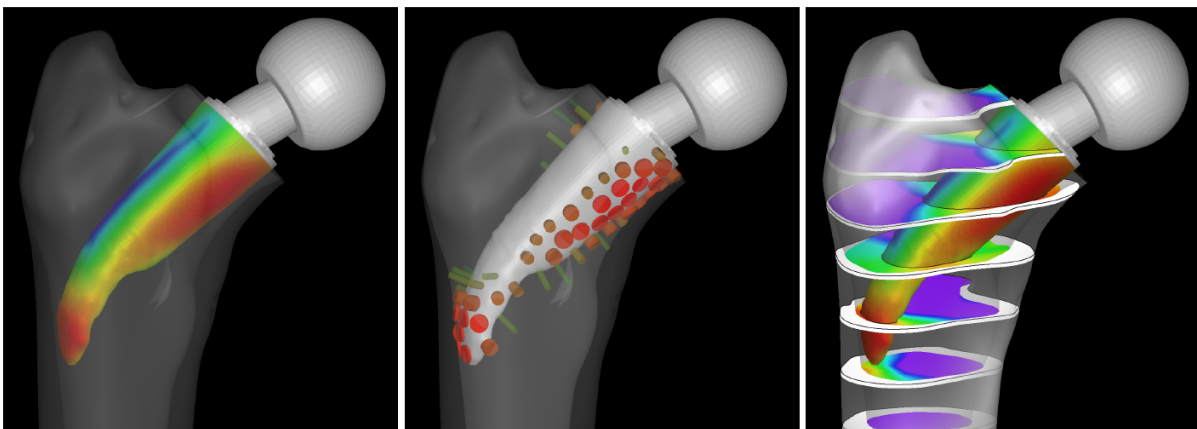


Figure 2.4: Distance visualisations using colour coding on the implant surface (left), oriented cylindrical distance glyphs (middle), and colour coding on the implant surface and on a set of axial slices (right) [37].

Due to their more complex situation in oncological pelvic surgical planning and thus risk of clutter, Smit et al. [40] decided to visualise distances by colour mapping and isolines.

In case of endoscopy and image-guided surgery, it is useful to highlight the distance between the instrument and the target or risk structure. Winne et al. [41] used a guiding line during endoscopy, indicating the distance of the target and pointer instrument by changing its colour every millimeter. Heinrich et al. [42] also introduced a colour-coded pointer ray from the tip of the instrument aligned with the tool axis. To detect surrounding structures, the second method, a side-looking radar, rotating around the instrument's tip was developed. Another method they proposed is a virtual lighthouse. The users can place the lighthouses at acquired positions, from where rays towards the instrument tip are emitted.

This overview has shown that there are several approaches and methods to visualise distances in medical applications. Nevertheless, distance visualisations have to be carefully chosen depending on the given application and task and thus they have to fulfill different requirements. The presented approaches still served as a basis and inspiration for the developed and evaluated distance concepts, that are introduced in the following.

The most basic feedback is to just display the value of the smallest distance between the clip and the vessels. This concept is easy to understand and provides the user with the exact numeric value. A large disadvantage is that the users do not know where this distance was measured. Accordingly, they do not know how to move the clip to avoid an unintended collision. In this simulation tool, the main function of the distance feedback is providing spatial information, which is not given by such a feedback. As a consequence, this concept was not used.

Drawing a colour-coded distance map on the anatomical structure is a common way that provides more information, which was for example also used by Suessmuth et al. [36] and Dick et al. [37]. Hereby, an adequate choice of the colour scale is essential, which will be discussed in Section 2.2.3. One obvious disadvantage of colour maps is that they only use colour. So for people who are colour-blind it is not applicable and the choice of the colour scale should consider common colour deficiencies. Distance maps display critical regions on the anatomical structure, but not on the medical device that is moved in the simulation. This information would be helpful to know the exact direction, thus the start and the endpoint of the corresponding distance, in order to navigate the device properly. Nevertheless, this concept was implemented and evaluated as it is a fundamental, intuitive and commonly used visualisation method.

To highlight the points that are chosen to calculate the distance, meaning the one on the anatomical structure and the one on the device, the following concepts were established. First, only the smallest distance between the vessels and the clip is visualised, which was also done by Winne et al. [41] and Heinrich et al. [42]. In this case, the smallest distance is depicted by using a cylinder instead of just a ray. The advantage of this is the cylinder radius can vary based on the distance, like Dick et al. [37] did with their cylindrical distance glyphs. Thus, large distances are still visible, whereas a single ray would be hard to recognize if the camera is relatively far away. As navigating the clip close to the vessels is the more important situation than when the clip is still far away, the cylinder should have a smaller radius for small distances. Otherwise it would occlude relevant structures. To highlight the approximate value of the smallest distance, the cylinder is

coloured according to the same colour scale as used for the distance map. This concept has the benefit that a near region highlighted by the distance map can be on the backside of the vessel and thus not recognizable by the user, whereas the cylinder can be seen, as the whole distance and not just one point on the vessel surface is highlighted.

One disadvantage of the cylinder is that it only shows the smallest distance. But during navigation, there can be several near regions that should be highlighted. Aside from that it can easily happen that the cylinder is occluded by the clip or a vessel. Consequently, a concept visualising all distances lower than a threshold was developed. Even if the smallest distance is occluded, the surrounding may be visible. As this concept displays many distances, using a cylinder for each distance would lead to occlusions and visual clutter. To prevent this, the distances are drawn as semi-transparent thin rays instead of cylinders. Heinrich et al. [42] also made their virtual lighthouse visualisation semi-transparent to avoid an obscured view.

All three visual feedback concepts can be seen in Figure 2.5.

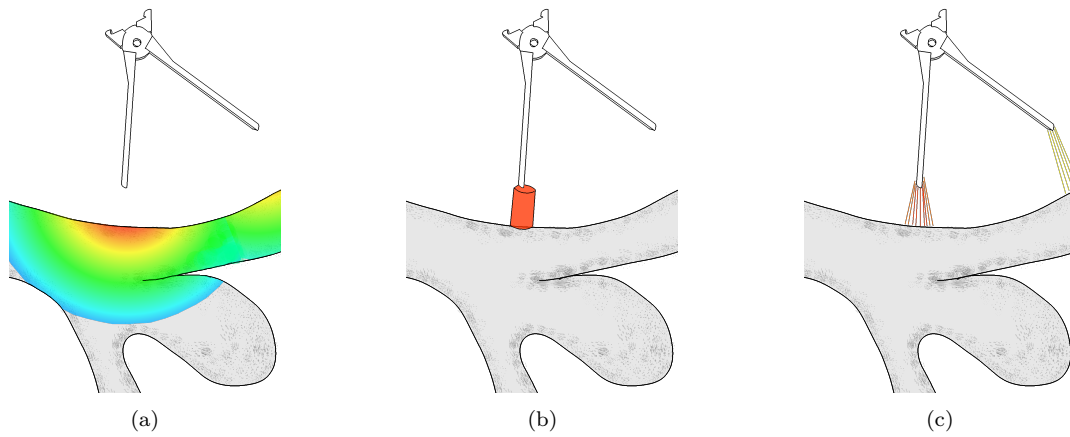


Figure 2.5: Concepts of visual distance feedback. (a) Distance map on vessel surface. (b) One cylinder representing the smallest distance. (c) Rays representing all distances smaller than a threshold.

Additionally to the above mentioned visual concepts, auditory feedback was considered. Various methods have been presented to show the user near regions. Depending on the concept, some distances are recognized more easily than others. Hence, a warning in form of sound was considered. This method was discarded, because it does not provide any spatial information, which should be the main function of this feedback. Furthermore, the clip is always navigated to the aneurysm and vessels and thus a sound will be perceived sooner or later during every clipping procedure.

2.2.2 Tractive Force Visualisations

As mentioned above, existing approaches for visualisation of aneurysms often show wall shear stress or blood flow. Saalfeld et al.'s [30] visualise the wall-shear stress on aneurysms to evaluate them. Meuschke et al. [43] proposed a combined visualisation of vessel deformation and hemodynamics. One concept is to unfold the aneurysm dome and visualise the deformation as colour map, and additional bars can visualise any scalar parameter, for example wall thickness. Another combination was to depict the wall deformation as a colour map on the aneurysm surface and additional isolines showing the wall-shear

stress. In another work Meuschke et al. [44] compared four glyph-based tensor stress visualisation techniques for cerebral aneurysms. Here, glyphs were chosen that should show the main directions of the stress tensors as well as the corresponding stress values along the main directions. The four compared glyphs, superquadrics, kite-shaped glyphs, streamlines and scatterplots, can be seen in Figure 2.6.

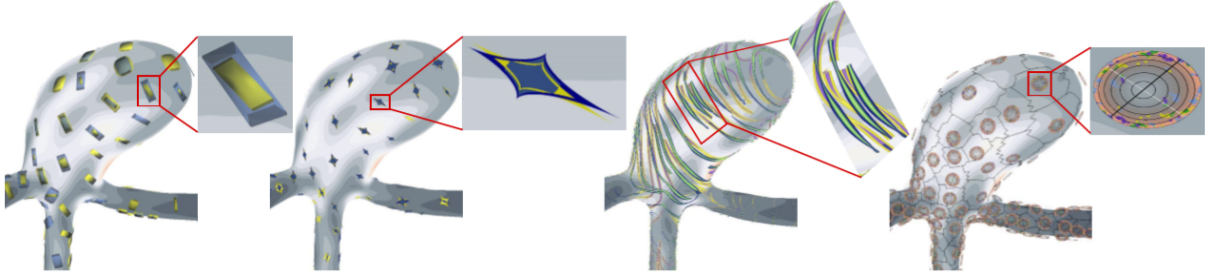


Figure 2.6: Glyph-based tensor stress visualisation. From left to right the following glyphs were used: superquadrics, kite-shaped glyphs, streamlines and scatterplots [44].

The mentioned approaches all visualise stresses and forces during the cardiac cycle, but there is no approach combining such visualisations in an aneurysm clipping simulation.

Another approach of stress tensor visualisation in the medical field was proposed by Dick et al. [45]. They introduced an interactive visualisation of stress tensor fields supporting the planning of hip joint replacement. Their approach is one of the first approaches allowing interactive visual exploration of time-varying 3D stress tensor fields. Figure 2.7 shows their resulting visualisation, aiming to provide spatial context as well as a detailed stress analysis.

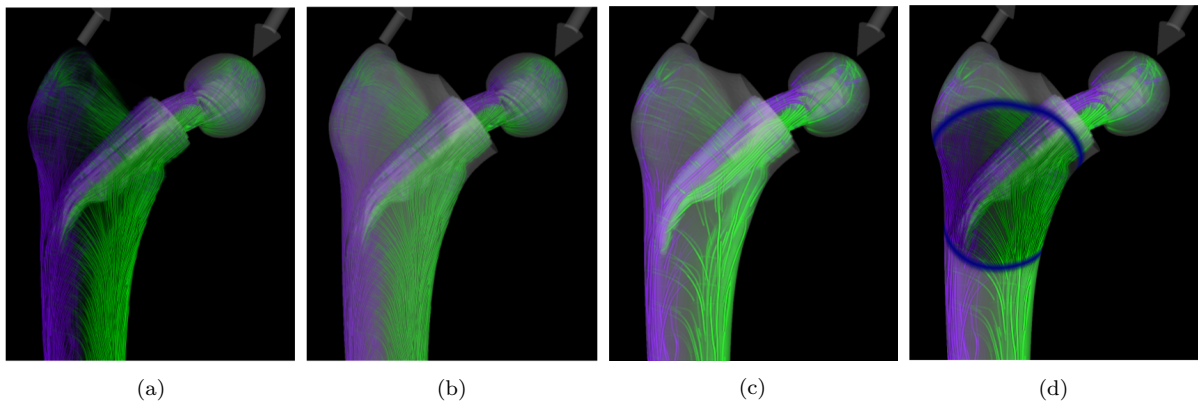


Figure 2.7: Visualisation of stress tensor fields. In *a*) the spatial context is not visible by just showing the stress lines. In *b*) the spatial context is given based on an increased opacity of the bone's surface, the tensor lines are washed out. Figure *c*) shows the result when fewer and thicker lines are shown. The global stress distribution is improved, but a detailed analysis is not possible. In *d*) a focus and context visualisation provides spatial context and global stress distribution, as well as a detailed stress analysis in the highlighted focus region [45].

The mentioned approaches of visualising force served as a basis for developing visualisations adequate for a clipping simulation tool. While doing so, it should be considered that the available information which should be visualised is not always the same.

The first tractive force visualisation concept arose from the widespread visualisation method to colour-code the surface. Hereby, each surface point can be coloured based on the displacement magnitude. This concept is intuitive but has the disadvantage that only the magnitude but not the direction of the displacement is shown. Therefore, a concept based on rays was introduced, which was also proposed by Dick et al. [45] for implant planning. The rays should run from the original position to the current position of each surface point. This visualisation has the disadvantage that long rays can occlude important information. Based on this, the third concept using glyphs was established.

Glyphs are small visual objects depicting attributes of a data record [46]. For this, different visual channels such as shape, size, etc. represent different data variables [46]. Some visual channels are more dominant than others, which should be considered in the design of the glyph [46]. For example, colour and size belong to the more dominant visual channels and thus have a pop-out effect, with colour having a stronger effect [47, 48, 49]. Consequently, important data variables should be mapped to colour. In the underlying case of tractive force, data variables are magnitude and direction. First, regions with high magnitude should be recognised and then the direction can be examined. Thus, magnitude is mapped to colour.

In general, it is possible to use very simple glyphs that are arranged densely, or to use few complex glyphs revealing a lot of information [46]. As there are only two data variables and an overall impression of the tractive force distribution should be conveyed, simple glyphs are used. This results in an overall impression drawing the user's attention to regions with strong displacements. This can be done by placing a glyph at the vertex's location of the surface mesh.

Based on this, the first concept of a glyph was developed based on the shape of an arrow. The displacement direction is shown by its orientation and the strength by its colour. In figure 2.8 the glyph is sketched. As all glyphs have the same size, they do not occlude each other like the rays and still depict both magnitude and direction.

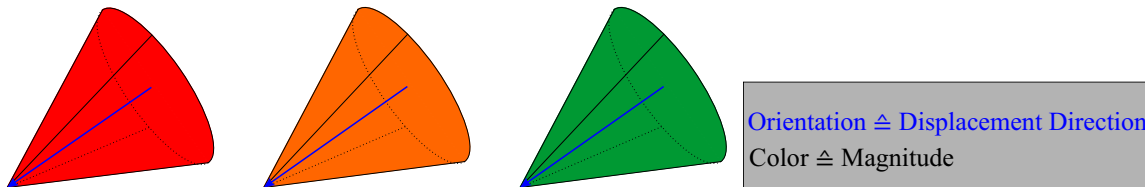


Figure 2.8: Sketch of an arrow glyph. Displacement direction is shown by the orientation (blue arrow) and the magnitude is mapped to colour. From left to right: increasing magnitude.

A second glyph was established, which highlights the strong displacements and hides the small ones, while maintaining the benefit that the simple glyphs do not occlude each other. This glyph has the shape of a drop and colour-codes the strength and orientation like the glyph before. Additionally, the glyph is scaled along its main axis according to the strength, resulting in longer drops representing strong displacements. To prevent strong displacements from occluding smaller ones, scaling the glyphs should only take place within a certain range. Furthermore, the glyphs are drawn semi-transparently corresponding to the strength. Both additional features ensure that strong displacements are more highlighted than small ones. The shape of a drop arose from the common flow visualisation technique oriented line integral convolution (OLIC) [50]. Here, drops of ink are smeared according to the underlying flow resulting in droplets with traces showing the

direction, orientation and magnitude of the flow [50]. Additionally, drops are a naturally occurring shape, which is why they are intuitive and easy to understand concerning their orientation. The glyph is sketched in Figure 2.9.

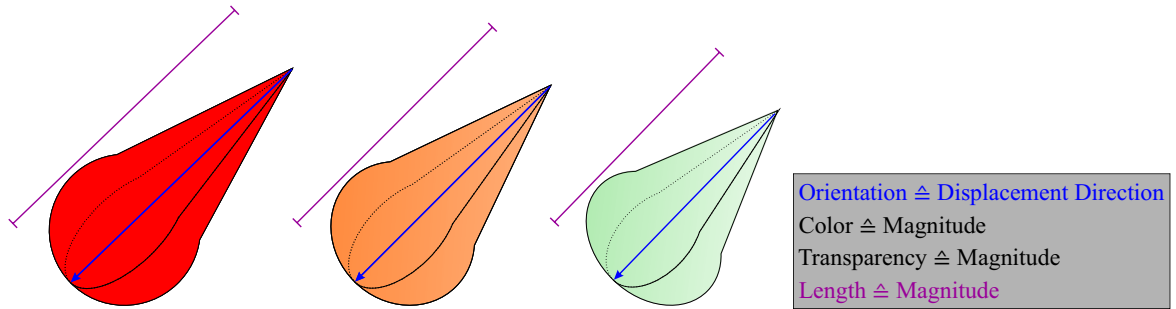


Figure 2.9: Sketch of a drop glyph. Displacement direction is shown by the orientation (blue arrow) and the magnitude is mapped to colour, transparency and length. From left to right: increasing magnitude.

All three above presented concepts of tractive force visualisation are sketched in Figure 2.10.

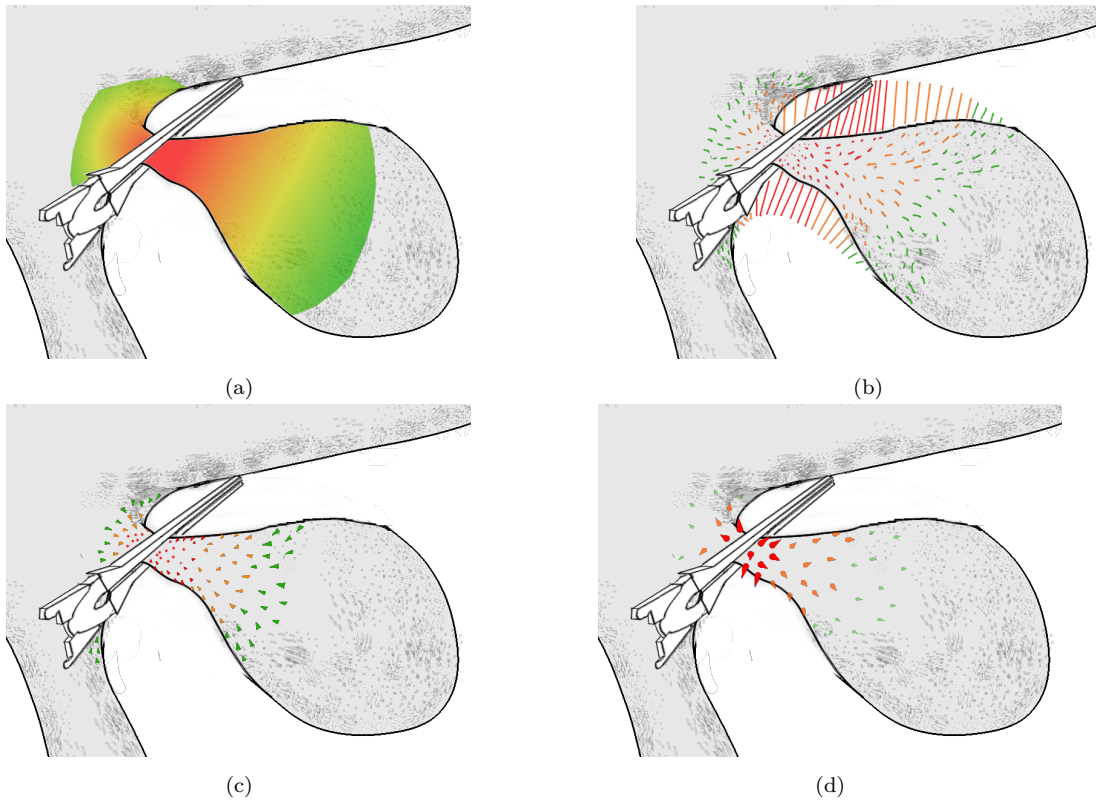


Figure 2.10: Concepts of tractive force visualisations. (a) Tractive force map on vessel surface. (b) Colour-coded rays from the original position to the current position. (c) Arrow glyphs indicating the direction and the strength. (d) Drop glyphs indicating the direction and the strength via multiple features.

2.2.3 Colour Scale

Colour is commonly used in data visualisation, as it is an easy way to convey important information. One major question when using colour is the choice of an appropriate colour scale, which mainly depends on characteristics of the data, the task and the target audience [51]. When talking about colour scales or colour maps, they can be divided into three categories: qualitative, sequential and diverging [52]. Diverging maps are used when a significant value near the median is represented [53]. Two different colours highlight the zero crossing in the data [51]. Using sequential maps, usually a scalar value is mapped to saturation, showing the order of the data [53, 51]. Qualitative colour maps, on the other hand, are used to represent nominal data, which can be categorized, but not ordered [53, 51].

Regarding the scalar values of distance and magnitude, a qualitative colour map is not appropriate. In both data there is no threshold or zero crossing, which argues against a diverging map. However, Moreland [53] mentions a few advantages of using a diverging colour map even if no significant median value should be highlighted. One advantage is that a more colourful and thus a more aesthetically pleasing visualisation can result [53]. This was also something the neurosurgeon said during feedback meetings. Besides realism and the clinical relevance, the tool should also be aesthetically appealing and be pleasurable to operate.

Furthermore, the data is visually divided into three logical regions by a diverging colour scale: low, mid-range, and high values. These regions additionally provide visual cues that help to understand the underlying data [53]. Depending on the chosen colours, some logical regions can be emphasised more than others, or can be associated differently. For example a green-red diverging scale can be used to draw critical values in red and less critical values in green, which is a common association. Another advantage of this map is that the order and combination of colours is common and intuitive due to its correspondence to the traffic lights going from green to orange to red. Because of these reasons, a green-to-red colour scale was chosen to visualise the distance and the magnitude. More precisely, large distances and low magnitudes are represented in green and low distances and high magnitudes in red, so in both cases the critical values are displayed in red.

One disadvantage of this map is that it is not usable for people with dyschromatopsia. Therefore, a second, alternative colour map like red-blue should be available in the tool, which is adequate for people with dyschromatopsia [53].

The rainbow colour map, which is commonly used in the visualisation community is not an appropriate option for the here underlying data. One main reason is the lack of perceptual order [54]. This idea was confirmed by the neurosurgeon, who asked what the different colours stand for when using a rainbow map.

2.3 Deformation

Nearly all medical simulations include a soft tissue deformation. Applying and closing the clip in the developed tool should lead to a deformation of the vessel model including the aneurysm. Therefore, two main conditions should be satisfied: real-time performance and physical correctness.

Fundamentally, there are a lot of different methods to simulate the behavior of soft tissue, but these can be divided into two categories, the finite element method (FEM) and

mass-spring model (MSM) [55].

FEM has the advantage that it is generally considered to be more accurate [55, 56], but its drawbacks include high computational costs which make real-time interaction difficult. Although there are several approaches to improve FEM to achieve better performance, the application of these approaches is still limited to relatively small and simple models [55]. Alternatively, the other physics-based method, the MSM, can be used. This method is not as accurate as FEM but it has a quite simple mathematical frame, high versatility for topological changes and a much better performance [55]. Different approaches aim to optimize the accuracy by improving the shape and topology. Another difficulty of MSM is that parameters such as the spring constant are not obvious, as they do not correlate with the actual material of the model [57]. Consequently, it is difficult to achieve suitable values for these parameters [55].

MSM was chosen as deformation method, as the performance, which is relevant in a real-time application, is much better. Another reason is the focus of this thesis being the distance and tractive force visualisations instead of developing a deformation as accurately as possible. Therefore, the faster and easier method was chosen as an initial method that can be further developed outside the frame of this thesis, if desired.

In general, MSM is made up of a set of masses connected by ideal weightless elastic springs [56]. Thereby, MSM can either represent just the surface or the volume of the deformable object. A volumetric model representing the surface and the internal structure, can be implemented through a tetrahedral mesh, like Mollmans et al. [58] proposed. However, such a volumetric method was not chosen, as it involves much higher computational costs [55].

Fundamentally, it is difficult to achieve good performance for real-time interaction and simultaneously accurate deformation. As the developed tool aims to provide basic understanding for physicians and trainees in the process of clipping, and as the main focus of this thesis is the distance feedback, it is more important to focus on the performance instead of accurate deformation. Thus, a surface MSM was chosen.

In the following, the concepts of surface MSM for the underlying application scenario is described. For constructing the model, the surface mesh of the deformable object was used. Each vertex of the surface mesh acts as a mass point and the edges represent the springs, which is illustrated in Figure 2.11. Generally, whenever forces act on masses, the masses are accelerated and consequently are displaced with a certain velocity. This process is described mathematically in the following part.

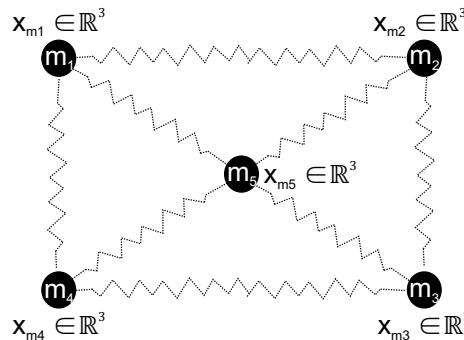


Figure 2.11: Masses m at their positions x , corresponding to the vertices of the surface mesh. According to the edges of the mesh, they are connected via springs.

Based on the initial positions of the masses, each spring has a resting length. Hence, the model consists of several parameters:

- The position of the masses $x \in \mathbb{R}^3$
- The masses $m \in \mathbb{R}$
- The forces $f \in \mathbb{R}^3$
- The spring resting length l_0

As a spring always connects two points, a force applied to one of these points results in two forces, one per point. Applying force to a spring results in a stretching or compression of the spring. Based on Hooke's law the elongation Δl depends linearly proportional on the force f . Written as a formula this means:

$$f = k * \Delta l \quad (2.1)$$

where k is the spring constant describing the stiffness of the spring. With this, the spring force acting on each mass point can be calculated. In addition to the springs between a point and all its neighbouring points, a spring between each point and its original position was included. Arnab et al. [59] used this spring for volume preservation, whereas in this case the spring is used to return to its initial shape. This force only acts if there is no collision and the aneurysm or part of the vessel returns to its initial state.

Another so-called internal force is the damping force. This damper acts against the velocity with which the masses are displaced [60]. The damper will be incorporated in the integration step, which will be explained after the external forces.

External forces are forces applied from the outside, like gravity, wind, or collision force. In case of the clipping tool, collision force is the only external force. For simplicity, a constant value can be used for the strength, and the direction equals the collision direction.

Based on the internal and external forces, the total force acting on a mass can be calculated by summing up the different forces:

$$f = f_{internal} + f_{external} \quad (2.2)$$

According to Newton's second law of motion, the motion of each point at time t can be calculated in the following way:

$$f(t) = m(t) * a(t) \quad (2.3)$$

where f is the sum of the internal and external forces, $m(t)$ is the mass at time t and $a(t)$ the acceleration at time t . The mass can be calculated by computing the area of each triangle and assigning one-third of it to each connected mass point. Since the mass and force are known and the acceleration $a(t)$ is the value that is searched for, the formula is rewritten as:

$$f(t)/m(t) = a(t) \quad (2.4)$$

The acceleration $a(t)$ is the second order derivation of the position and can be written as $\frac{dx(t)}{dt}$. Thus, the forces can be simulated over time based on the positions and masses:

$$f(t)/m(t) = \frac{dx(t)}{dt} \quad (2.5)$$

There are several integration methods to solve the above differential equation, which can be divided into explicit and implicit methods. In general, explicit methods are fast but they have stability problems and are prone to failure, whereas implicit methods are unconditionally stable and much more time-consuming because they have to solve large systems of equations [61]. For implicit methods, larger time steps can be used, however this can reduce the accuracy [62]. Because of these disadvantages, an explicit method was chosen.

The most basic explicit integration is the Euler integration, which has a very simple computation but it is inherently unstable. Only with a very small time step and forces remaining within reasonable limits, the simulation would be stable and realistic. As the following two formulas show, only the current position ($x(t + \Delta t)$) and velocity ($v(t + \Delta t)$) are used:

$$x(t + \Delta t) = x(t) + \Delta t * v(t) \quad (2.6)$$

$$v(t + \Delta t) = v(t) + \Delta t * \frac{f(t)}{m} \quad (2.7)$$

Another method is the so-called Verlet integration. Here, not just the current position but also the previous position are used. In the classic Verlet integration no velocity is calculated. The velocity is thereby approximated by the current and previous positions:

$$x(t + \Delta t) = 2x(t) - x(t - \Delta t) + \frac{f(t)}{m} * \Delta t \quad (2.8)$$

There are several extensions to this basic formula. One example is the so-called Velocity Verlet. If the velocity is needed for additional physical calculations this Verlet method can be used to not only determine the position but also the velocity. Mor [63] used a Verlet integration for surgical simulation and therefore he has compared Euler, Runge Kutta 4 and two different Verlet integration methods regarding to their computational efficiency. This comparison shows that the Verlet methods perform much better than the other two. As the Verlet integration seems to be a good and often used explicit method, it was also used in this thesis.

As mentioned before, the damping force slows down the velocity, which is not calculated in this case. Consequently, the damping force has to be included directly in the integration step, which is for example done by Halic et al. [64], resulting in this final formula with k_d as the damping constant:

$$x(t + \Delta t) = x(t) + (x(t) - x(t - \Delta t)) * (1 - k_d) + f(t)/m * \Delta t * \Delta t \quad (2.9)$$

2.4 Collision

The most important part of internal physics to provide realistic simulation are collisions, preventing two objects from moving into each other. As there is only one moving object, the clip, collisions can only take place between the clip and the vessels with the aneurysm and the skull, respectively.

In general there are several ways to perform collision detection. One possibility is to use bounding boxes, or other shapes. This is an efficient way if a simple form, such as a box or sphere, is used as a collider. But if a more precise collision is required and the object does not have a simple geometric shape a mesh collider is necessary. Depending on

the mesh and thus on the object's shape, the mesh can be concave, which leads to more expensive collision detections. In such a case, collision can be performed by ray casting. Ray casting is widely known in the field of computer graphics, rendering 3D scenes and volume visualisation. The main principle is casting rays and sampling along the ray [65]. For example Shin et al. [66] used this method for detecting collisions in virtual endoscopy and Vlasov et al. [67] used ray casting for collision detection in context of haptic feedback. Ray casting can also be used, starting from one object. Then, the vertices of the mesh serve as starting points and the corresponding normals as directions. It should be considered, that the positions and normals of the vertices are in the object's coordinate system. Because of this, performing ray casting starting from the vertices would require converting the positions and normal vectors into world coordinates each frame. To avoid these transformations, the object's coordinate system can be set to the world coordinate system. In addition to this, it is important to choose an object that has a relatively dense mesh, otherwise the amount of rays, meaning the sampling rate, would be too low. In this case, additional starting points have to be calculated.

2.5 Aneurysm and Clip Models

Based on the application area, the simulation consists of three types of models: a skull, Circle of Willis with aneurysms and clips. As the skull is only used for orientation and the craniotomy, a unit skull was used. To provide an appropriate variety of models a careful selection was carried out in close cooperation with the expert.

Aneurysm Models For such a simulation it is relevant to use realistic and appropriate aneurysms. This means that it is important to include aneurysms which would be treated by clipping. Based on the comprehensive work experience of the neurosurgeon, also serving as a contact person during the development, middle cerebral artery (MCA) aneurysms are often treated by clipping. More precisely, MCA aneurysms located at the M1, M2 bifurcation, that are highlighted in Figure 2.12 were chosen. This figure shows different locations of MCA aneurysms and their frequency. These aneurysms are the most common MCA aneurysms [68] and are usually treated by clipping [13]. This finding was further enclosed by the medical cooperation partner.

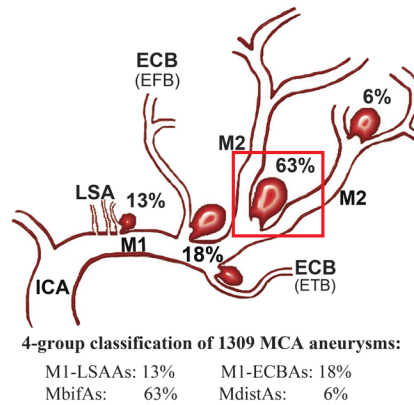


Figure 2.12: The distribution of 1309 middle cerebral artery (MCA) aneurysms along the MCA following a 4-group classification [68]. The chosen type for the simulation tool is highlighted.

Consequently, MCA bifurcation aneurysms were chosen as representative models. Based on Kato's [13] classification five different types of these aneurysms were selected. According to Kato [13], their classification is based on morphological features, influencing the techniques of clipping. This classification is much more useful in pre-operative planning, than classifications based on size, location or pathology that serve to describe aneurysms [13]. During the cooperation with the experienced neurosurgeon, the possible implementation and adequacy of the cases in a clipping simulation for training were discussed individually. Consequently, five different, representative and well discussed aneurysm type were chosen, ensuring a diverse and appropriate selection in the clipping simulation tool.

Below, the five types that were created are presented:

The first type is an circumscribed bulging without any extension to M1 in proximal direction [13]. An intraoperative image and drawing of such an aneurysm can be seen in Figure 2.13.

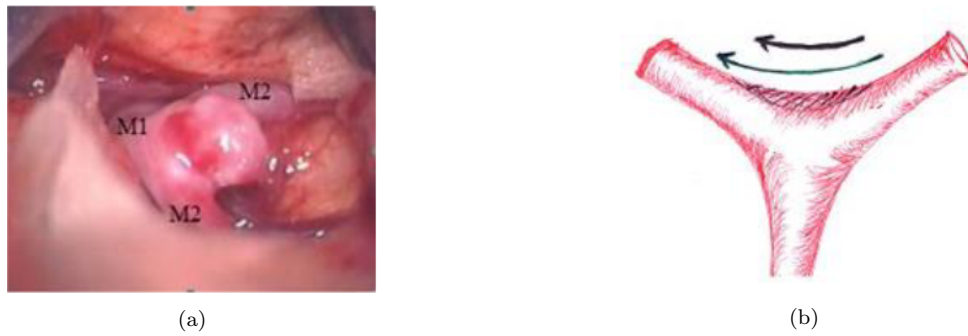


Figure 2.13: MCA aneurysm type 1. (a) Intraoperative image. (b) Drawing of type 1. The green arrow is representing the axis of the M2 branches, the black arrow is representing the axis of the aneurysm's neck [13].

The second type (see Figure 2.14) is extending to portions of M1 proximally. Thus, they are often saddling over the bifurcation and have a long axis of orientation perpendicular to the axis of M2 branches. Consequently, they have a much more complicated neck, orienting in multiple planes, than the aneurysms of type 1 [13].

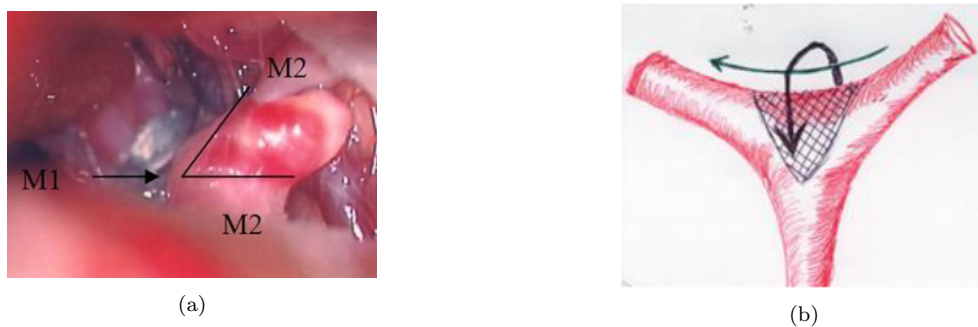


Figure 2.14: MCA aneurysm type 2. (a) Intraoperative image. (b) Drawing of type 2. The green arrow is representing the axis of the M2 branches, the black arrow is representing the axis of the aneurysm's neck [13].

Type 3 aneurysms, shown in Figure 2.15, additionally have a perforator or branch emerging at the neck.

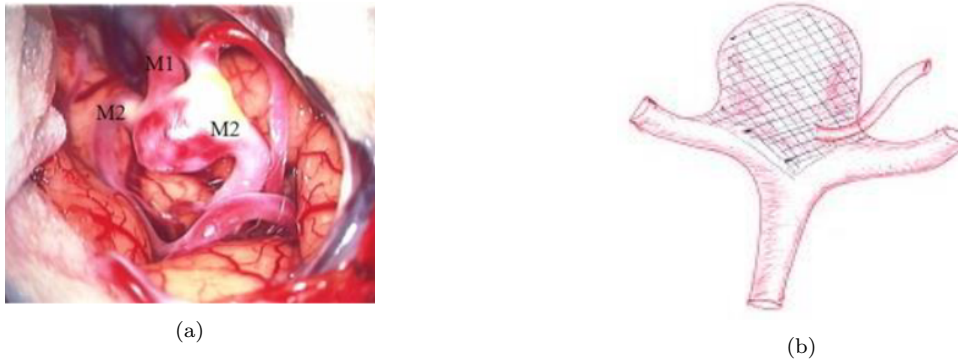


Figure 2.15: MCA aneurysm type 3. (a) Intraoperative image. (b) Drawing of type 3 [13].

Aneurysms belonging to the next type, meaning type 4, are often giant aneurysms, where the M2 branches seem to arising from the aneurysm rather than M1. As the wall of M1 and/or M2 are involved, the reconstruction of the bifurcation is required [13]. Such a case is shown in Figure 2.16.

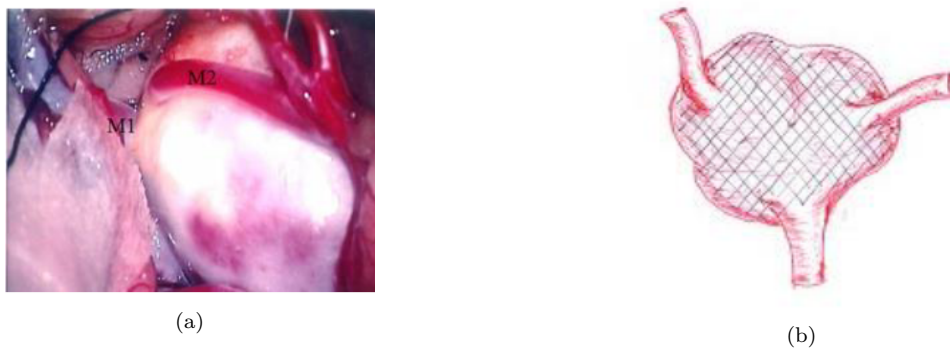


Figure 2.16: MCA aneurysm type 4. (a) Intraoperative image. (b) Drawing of type 4 [13].

Type 5 are so-called blister aneurysms (see Figure 2.17). These are rare arterial lesions which are not located at branching sites. In contrast to other aneurysms they are very small and have a very fragile aneurysmal wall [69].



Figure 2.17: MCA aneurysm type 5. (a) Intraoperative image. (b) Drawing of type 5 [13].

Clip Models The clip models integrated in the tool are based on L-aneurysm clips of Peter Lazic¹. The above mentioned neurosurgeon selected all clips of this product category that are similar to the clips available at the University Hospital Magdeburg. Accordingly, clips were selected that are frequently used in real clipping surgeries. In Table 2.1 all selected clips and their characteristics are listed.

Table 2.1: Overview of all selected clips and their characteristics.

Product key	Type	Max. opening	Jaw length
45.740	standard (straight)	08.0mm	07mm
45.750	standard (straight)	08.9mm	09mm
45.760	standard (straight)	10.2mm	12mm
45.780	standard (straight)	12.2mm	15mm
45.790	standard (straight)	13.3mm	18mm
45.782	standard (curved)	12.2mm	15mm
45.747.15	standard (curved)	12.2mm	15mm
45.747.18	standard (curved)	13.3mm	18mm
45.761	standard (angled)	10.5mm	12mm
45.748	standard (angled)	09.5mm	07mm
45.759	standard (angled)	13.6mm	12mm
45.870	paddle	12.3mm	15.7mm
45.599	fenestrated, 3.5mm (straight)	08.4mm	05mm
45.620	fenestrated, 3.5mm (straight)	12.0mm	12mm
45.624	fenestrated, 3.5mm (angled)	04.9mm	10mm
45.640	fenestrated, 5.0mm (straight)	10.2mm	06mm
45.650	fenestrated, 5.0mm (straight)	11.6mm	09mm
45.644	fenestrated, 5.0mm (angled)	06.1mm	05mm

¹Peter Lazic GmbH Microsurgical Innovations, Tuttlingen: <https://www.lazic.de/>, date: 10.08.2020

2.6 Graphical User Interface and Interactions

The tool comprises five different scenes. Aside from a start scene, there is a scene for selecting the aneurysm, performing craniotomy, a scene for clipping and finally a comparison scene. All five scenes and their user interface components can be seen in Figure 2.18 below.

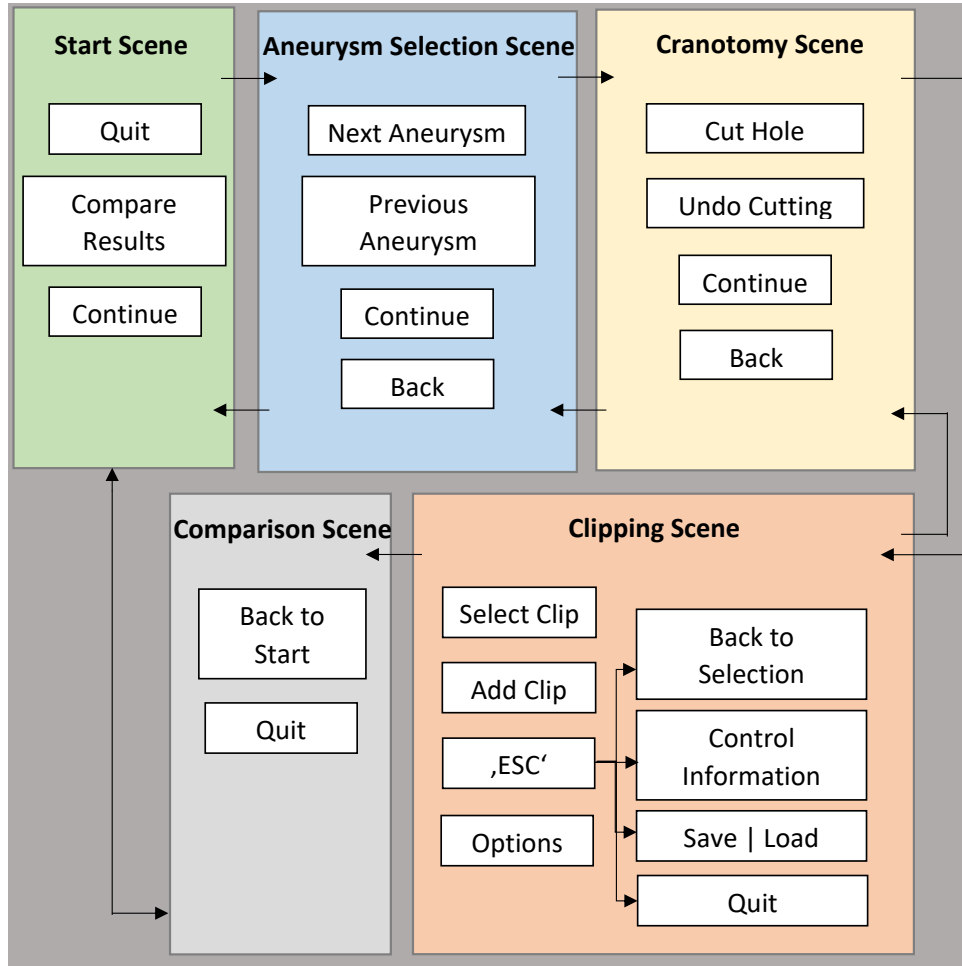


Figure 2.18: Overview of the scenes and user interface.

After the start scene, the user has to select an aneurysm based on a given selection. The chosen aneurysm is then used for the craniotomy. There the user has to select a place and size to cut the skull. The resulting hole is used as the starting situation for the clipping process. In the clipping scene the user can change the clip and has the possibility to set some options. By pressing the escape-button, a menu appears. Here the user can choose between quitting the tool, reading control information, saving the result and going back to the aneurysm selection. In the scenes where the 3D-model of the aneurysm is shown, the user can move the camera, more precisely translating, rotating and zooming, enabling a proper view. In the clipping scene the most important part is interacting with the clip. Thus, the user is able to translate, rotate and open and close the clip. Starting from the start scene or the clipping scene the user can load two saved files to compare them in the comparison scene.

2.7 Requirements

At the beginning of this work, several requirements have been set. They derived from several meetings with the neurosurgeon, where different cases and surgeries were discussed, and from analysing the state of the art. The requirements can be categorized into two groups, requirements for the different visualisations and requirements for the tool in general.

Table 2.2 lists and describes specific requirements, the distance and force visualisation concepts have to meet.

Table 2.2: Overview of requirements for the visualisation concepts.

Requirement	Description
Prevent Occlusions	The visualisation should not occlude important information. The vessels should always be visible, so the user can still observe the course of vessel and their shape.
Unobtrusive	The visualisation should not hamper the user. Therefore, the feedback should always be unobtrusive, so the main focus is still on the vessel and clip. Appropriate interactions with the device, meaning the navigation and closure of the clip, and completing the task should always be possible.
Added Value	The visualisation should create added value. In terms of distance information this means facilitating the navigation of the clip. This includes that the feedback is always available and correct. Regarding the tractive force feedback regions with high force should be highlighted and clearly visible.
Intuitive	The visualisation should be intuitive and easy to understand, so no learning is required. This refers to each visualisation concept as a whole, but also to the underlying colour scale.

Furthermore, the general requirements for the tool are listed and described in Table 2.3. The first four requirements refer to different scenes that are necessary to enable a complete clipping simulation tool. Subsequently, there are the three non-functional requirements performance, realism and usability.

Table 2.3: Overview of requirements for the simulation tool.

Requirement	Description
Aneurysm Selection Scene	The user should be provided with a selection of different and relevant aneurysms.

Requirement	Description
Craniotomy Scene	Besides the aneurysm selection, the tool should also contain a craniotomy scene. Here, the user should be able to specify the location and size of the hole.
Clipping Scene	The most important scene is the clipping scene, in which the user can navigate a clip and apply multiple clips to the selected aneurysm.
Comparison Scene	With the help of a comparison scene, the user should be able to compare two different clipping results.
Performance	The performance of the tool should enable a fluent procedure. This means situations requiring high computational effort should not hamper the interactions and the workflow.
Realism	Physical processes, such as the deformation or clip movement, should be simulated realistically enough in order to be still reasonable for the user. Additionally, all models should be realistic in terms of anatomy and technical data.
Usability	<p>For the user it should be easy to interact with the tool. Thus, the workflow of the tool should be kept simple and the tasks and possibilities in the different scenes should be easy to understand. Most important for the usability of a simulation tool is the interaction. Interacting and navigating the clip as well as the camera should be as intuitive and easy to learn as possible. According to the ISO 9241-11:2018 in Ergonomics of human-system interaction — Part 11: Usability: Definitions and concepts [70], usability is made of efficiency, effectivity and satisfaction:</p> <ul style="list-style-type: none"> • Efficiency: The user should be able to accomplish the tasks with an appropriate effort, meaning within a reasonable time. • Effectivity: The user should be able accomplish the tasks with few errors. Errors can be for example navigating in wrong directions, many unintended collisions or closing the clip while it is not at the expected position. • Satisfaction: The extend of coincidence of physical, cognitive and emotional reactions of the users with user requirements and user expectations to such a simulation.

Based on these requirements, a clipping tool for aneurysm with different visualisation concepts were created.

3 Implementation

In this chapter the implementation of the previous concepts will be described. The whole implementation was conducted in the game development platform Unity¹ 2019.3.4f1 and the development environment Visual Studio 2019². The programming language was C#. At the beginning of this work it was considered to implement the simulation as a virtual reality application, which was done in most of the approaches presented in Section 2. This was rejected for two reasons. One reason is that a training simulation should be available in a clinical environment and accessible for as many people as possible, which is given with a simple and cheap desktop application, and is not given with an expensive virtual reality application. The second reason is that the focus of this work is on developing and evaluating visualisation concepts, which can also be done with the help of a desktop application and they can still be adopted to similar virtual reality applications.

3.1 Graphical User Interface and Interactions

This section serves to give a detailed overview of the workflow. Accordingly, the different scenes comprised in the tool and the possible user interactions are described. The different scenes and the workflow can be seen in Figure 3.1.

After the start scene (Figure 3.1 (a)), the user can select one aneurysm of the selection presented in the next section (Figure 3.1 (c)). The vessels with a corresponding aneurysm are placed into a semi-transparent skull. The transparency of the skull can be changed in all scenes, in which it is displayed.

The selected aneurysm is now shown in the craniotomy scene (Figure 3.1 (c)). Here the user has to click on the desired place on the skull to perform a craniotomy. Via ray casting starting from the mouse position the exact click position on the skull is determined. This click position is the center of the craniotomy. In the clipping scene, the clip has to be moved into the skull via the hole (Figure 3.1 (d)). To achieve this, the mesh collider of the skull has to be adapted so no collision occurs at the hole. Otherwise the clip could not enter the skull. To enable collision with the skull, but not the hole, corresponding vertices of the mesh collider have to be deleted. As changing a mesh and updating a mesh collider is time-consuming, the area around the click position is first simply highlighted in blue. This is done by first finding all vertices within a specific radius around the click position, changing the vertex colour of these vertices and then passing this information on to a vertex shader.

The user can change the position by another click and can adapt the radius of the area

¹Unity Technologies, San Francisco: <https://unity.com/de>, date: 06.06.2020

²Microsoft Visual Studio: <https://visualstudio.microsoft.com/de/>, date: 06.06.2020

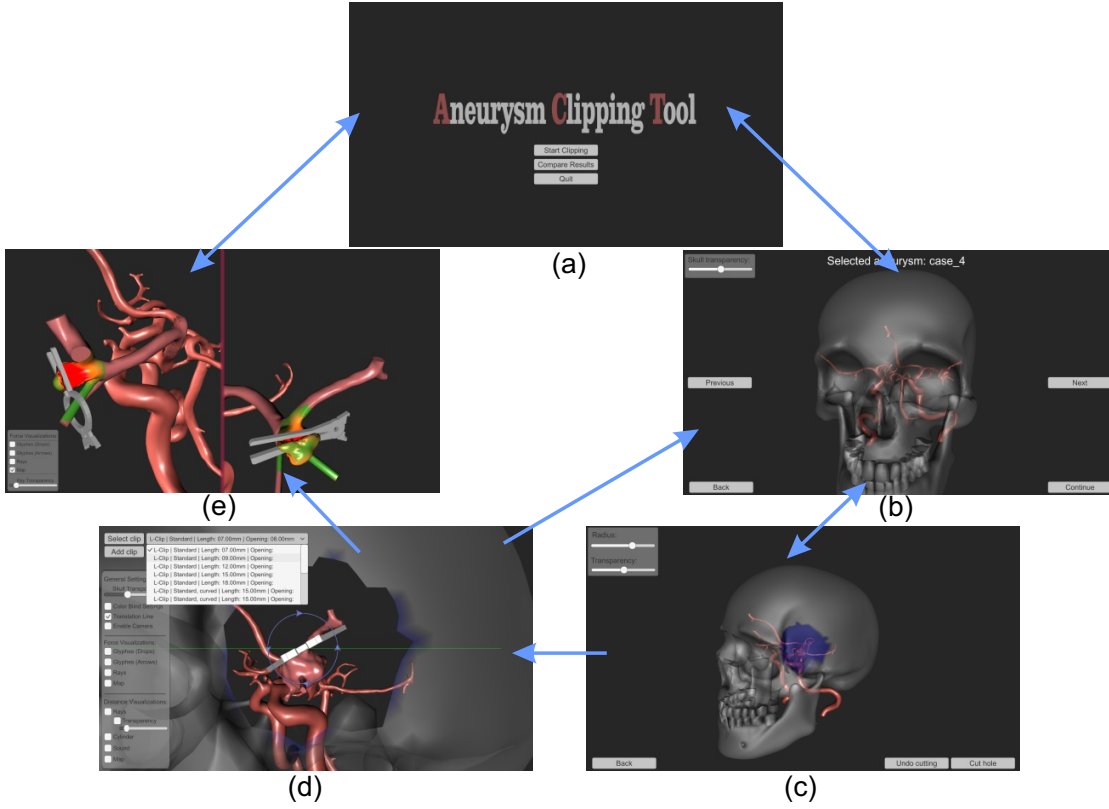


Figure 3.1: Overview of the different scenes: (a) Start scene, (e) comparison scene, (b) aneurysm selection scene, (c) craniotomy scene and (d) clipping scene. The blue arrows indicate the transitions between the different scenes.

via a slider. By affirming the position, a hole is cut into the mesh of the skull. Cutting a hole whenever the user clicks on the skull instead of just highlighting the potential hole would require modifying the mesh more often. As the initial mesh was saved, the cutting can be undone and a new location or radius can be chosen.

In both scenes, the aneurysm selection and craniotomy, it is essential that the user can inspect the aneurysm. Here the user can freely rotate and translate the camera, and zoom in and out. Additionally, there is a slider to change the transparency of the skull, so the user can set it according to their interest and need.

As the vessels are entwined, it is not easy to find a general location for lighting resulting in appropriate shadows for a good 3D view and that also ensure that each aneurysm is well visible. This is especially important because the user can freely rotate the camera. As a consequence of this, a light was attached to the camera, ensuring that the front is always illuminated.

To enable a more realistic setting, the free camera movement is disabled in the clipping scene, as in a real surgery the field of view is also limited. Instead, the camera is automatically placed according to the craniotomy, facing the hole with a specific offset. Here the user can zoom in and out and translate and rotate the camera within a certain range. The range in which the user can translate the camera is calculated based on the craniotomy. The distance d between the translated camera position p and the line defined by the center c of the hole and the skull's surface normal n at the center point is calculated by:

$$d = \frac{|p - c \times n|}{|n|} \quad (3.1)$$

If the distance is bigger than the radius of the hole, the translation is stopped by setting the camera position to the previous position. When the user wants to rotate the camera, this can be done within a range of $+/- 45^\circ$. Without these limitations it would be possible to move the camera into the brain from a position other than the hole. Thus, the aneurysm could be seen from other points of view, that are not feasible in a real surgery and consequently are not realistic.

By entering the clipping scene (Figure 3.1 (d)), the users are viewing the hole and are having a clip in front of them. Provided that there is enough space, this clip can always be changed by a drop down menu which is visible in Figure 3.1 (d). Checking if there is enough space is done by changing the clip without making the new clip visible. Via ray casting starting at the vessel surface and casting it to the inside, it is then verified whether the new clip would protrude into the vessels. If so, the user is informed by a text and the new clip is displayed as a red hologram for a few seconds. This way, the user can see the size and shape of the new clip and can see where it protrudes the vessels. By default, the drop-down menu is hidden and appears if the ‘Select Clip’-button is pressed. The drop-down menu can be hidden by pressing the button again.

The most essential part in this scene is moving the clip. First, this was done via rotation and translation handles that were placed directly at the clip, as they are a common way to interact with 3D-models in 3D-graphic software. During an intermediate evaluation with the neurosurgeon, it became apparent that this way of interacting is not intuitive but rather confusing for people who are not familiar with interactions via handles, like probably most medical doctors are. Consequently, the way of interacting was changed to an interaction via keyboard. The common keys ‘W’, ‘A’, ‘S’ and ‘D’ are used for clip translation in the screen plane. Additionally, the keys ‘E’ and ‘Q’ are used for depth movement towards and away from the user. To support the movement, a semi-transparent green auxiliary line is displayed at the clips location when pressing one of these buttons. The line that can be seen in Figure 3.1 (d) represents the axis along which the clip is moved. Closing and opening the clip is done via the up and down arrows. Rotating the clip around the axis going out of the screen is done via a handle placed at the clip. All other rotations are done via tilting the clip with the left mouse button around the desired axis. This axis is obtained by the cross product of the mouse movement direction and the viewing direction of the camera. The resulting vector lies in the screen plane orthogonal to the mouse direction.

As there are many cases in which several clips are used to treat an aneurysm, the option to add a clip was implemented. After adding a new clip, the previous clip can not be changed anymore, which is a reasonable constraint, since according to the neurosurgeon’s statement it is not common to apply and remove clips during surgery multiple times.

By pressing the escape-button, the user opens a small menu. Here, the user can go back to the aneurysm selection, read the control information, save or load a clipping result and quit the application.

From the start scene or the clipping scene the comparison scene (Figure 3.1 (e)) can be entered by selecting two saved clipping results. Both results are presented by a split screen, enabling a direct, clear and detailed comparison. This is also supported by a free camera movement. In this scene, the clip cannot be changed anymore, the user can only enable the different tractive force visualisations to compare the clipping methods based on the force information.

In the clipping scene and the comparison scene, there is a menu list with different options on the left side of the screen. In the clipping scene, the different options are separated

into three categories: general settings, force visualisations and distance visualisations (see Figure 3.2). The general settings include setting the skull transparency, changing the colour map to a dyschromatopsia-friendly scale and disabling the translation auxiliary line. Additionally, the different distance and tractive force visualisations can be enabled and disabled. For the distance visualisation via rays, additional settings regarding the ray transparency are available.

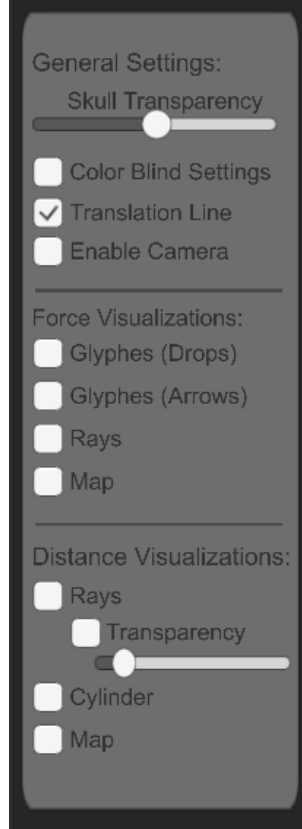


Figure 3.2: Settings available in the clipping scene.

The layout of this setting panel was created by applying common Gestalt principles. Particularly, the principle of proximity [71] and the principle of common regions [72] are exploited. According to these principles, options belonging together are placed near to each other and are situated in the same separate region. Thus, the three categories are visually separated resulting in a clear layout.

In the comparison scene only options concerning the force visualisations are available.

3.2 Aneurysm and Clip Models

Aneurysm Models As the clipping simulation tool should serve as a training possibility, no real data was used. Instead, five different and relevant cases of MCA bifurcation aneurysms were modelled in cooperation with the neurosurgeon, making use of his experience and knowledge, recall Section 2.5. The models were constructed during meetings with the neurosurgeon. He supervised the whole modelling process and issued instructions

to obtain as realistic and sophisticated aneurysm models as possible.

Modelling the aneurysms was done by using a healthy Circle of Willis. This Circle of Willis is a segmented 3D-model based on real MRA (magnetic resonance angiography)-data. At the corresponding location, the vessels were bulged with the 3D-modelling software Sculptiris³ to form the aneurysm. Figure 3.3 shows the different resulting aneurysm models.

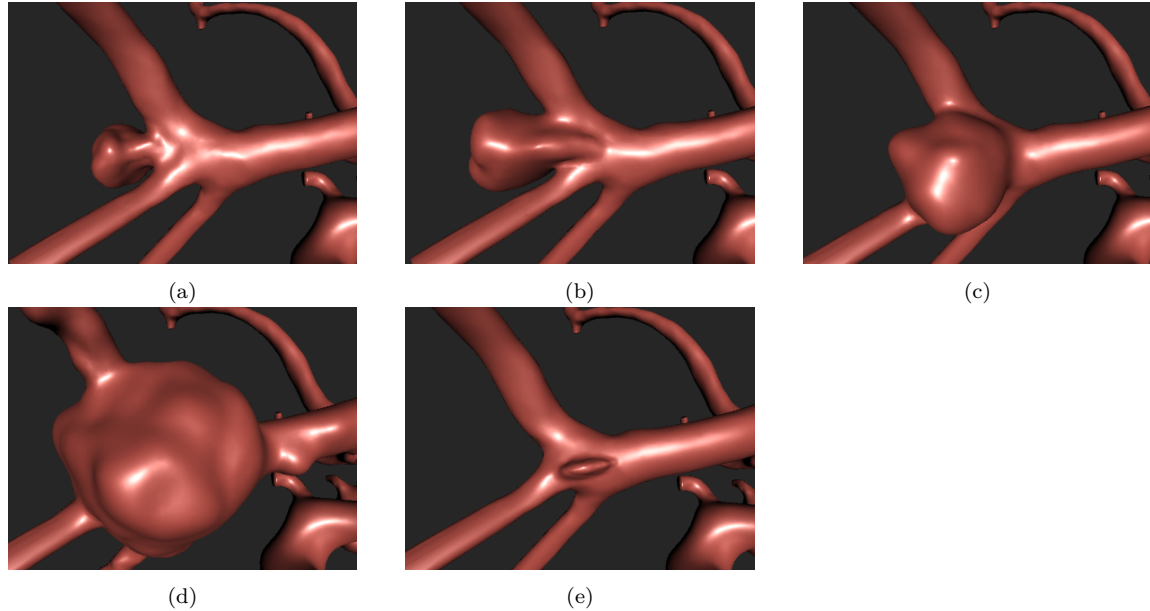


Figure 3.3: Final models of the five ((a)-(e)) different MCA bifurcations classes.

Clip Models Based on a product catalogue, the clips mentioned in Section (2.5) were built in Blender⁴ Version v2.79. Not all of the relevant data were given by the product catalogue, so not all measurements were entirely correct, but the jaw length and dimension of opening correspond to the technical drawings. Figure 3.4 shows the technical drawing and the final model of one example clip. Furthermore, the clinical expert was very satisfied with the resulting models.

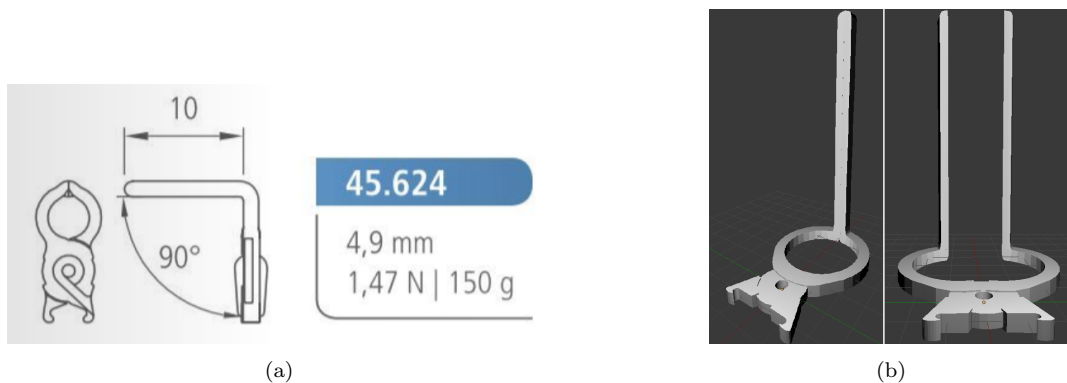


Figure 3.4: (a) Technical drawing and (b) realization of an example clip.

³Pixologic, Inc, Los Angeles: <https://pixologic.com/sculptris/emails/operating-system.php>, date: 17.09.2020

⁴Blender, Amsterdam: <https://www.blender.org/>, date: 17.09.2020

3.3 Physics

In the following, the implementation of physics, including collision and deformation, is described.

3.3.1 Collision

During the whole simulation process, two different ways of collision detection were used. To have an efficient detection, the underlying colliders should be as simple as possible. This is possible for the clip models, as their subparts are made of simple geometries and thus simple compound colliders can be used. In contrast to this, the collider of the vessel section has to be much more complex, as the vessels are convex objects and it is important that the collider represents the shape exactly. Therefore, a mesh collider is used for the vessel section. Based on these two colliders, collision detection during clip rotation and translation is determined by the unity physics engine.

However, this can not be used while the clip is closing and the vessels are deforming, because it would require an update of the mesh collider after each deformation, which is extremely time-consuming. That is why a new collision detection based on ray casting is performed during this process. For this, the unity ray cast method was used to shoot rays from vertices of the vessel mesh in their corresponding normal directions. By hitting a collider of the clip within a certain distance threshold, a collision is detected. This method does not require an update of the mesh collider, because only the ray and the target, in this case the clip, colliders are needed. For building the rays the updated, displaced vertices and normals of the vessel mesh are used.

Performing raycasting for tens of thousands of rays each frame is also very time-consuming. This can be reduced by restricting the amount of rays. It is not necessary to perform ray casting for each vertex, as only vertices close to the clip can potentially collide. Hence, vertices are only used if their distance to the clip is smaller than a threshold. Another way to increase the performance is conducting the ray castings parallelly by using unity's RaycastCommand⁵ method to perform ray casts asynchronously and in parallel to each other during a job.

3.3.2 Deformation

As explained in Section 2.3, the deformation based on a mass spring model mainly consists of the following parameters:

- The position of the masses $x \in \mathbb{R}^3$
- The masses $m \in \mathbb{R}$
- The forces $f \in \mathbb{R}^3$
- The spring resting length l_0

⁵Unity Technologies, San Francisco: <https://docs.unity3d.com/ScriptReference/RaycastCommand.html>, date: 16.09.2020

For the following deformation calculations, a few values can be precomputed for the selected aneurysm, so they can be calculated and saved once instead of calculating them in each iteration.

First, the masses m_i of the mass points are calculated. As mentioned before, the mass points are located at the vertices' positions of the surface mesh of the vessel section. Consequently, the mass of one mass point can be calculated by summing up one-third of the area of each connected mesh triangle. Since the corner points of each triangle are determined by the vertices' positions, the length of each side of the triangle is given by the euclidean distance. Thus, Heron's formula is used to calculate the area. One-third of the resulting area is added to the mass of each connected mass point:

$$m_i = \sum_{\forall \Lambda} \frac{1}{3} * \sqrt{s * (s - a) * (s - b) * (s - c)} \quad (3.2)$$

where Λ is a triangle connected to mass point i , s is $\frac{a+b+c}{2}$ and a , b and c are the sides of the triangle.

Furthermore, the spring rest-length l_0 is precomputed by calculating the euclidean distance between each neighbouring pair of vertices.

As mentioned in Section 2.3, the time step is an important parameter in the implementation of the deformation. On the one hand, the time step should be as small as possible to reduce the error resulting from the integration. On the other hand, a small time step leads to high computational costs and thus performance problems. After testing different values, a fix time step of 0.02 seconds of the time in the tool was chosen, minimizing the error while preserving a fluent procedure. Another factor influencing the performance is the amount of masses and springs and thus the number of calculations per iteration. Because of this, not all vertices of the object are considered in the deformation. Once the clip is colliding with the vessel, near vertices are marked as deformable. These vertices are selected by their euclidean distance to the collision point. Accordingly, the calculations in the deformation are only conducted for deformable vertices.

A collision entails an external force being exerted on the colliding vertices. To reduce computational costs, only collisions during the closure of the clip entail a deformation of the vessels. To define the external force acting on a vertex, the closing directions of the clip wings and the negative normal of the vertex colliding with the clip are required. Additionally, the assumption that no dynamic friction between the clip and the vessels exists was made. This leads to inward deformations along the vertices' negative normals, but the vessel surface is not pulled by the external force. Otherwise, the vessel surface would be pulled strongly to the side, which is not realistic, as the vessels are wet and not sticky. Based on this, the force applied to a vertex is calculated in the following way, which is also illustrated for three cases in Figure 3.5: The normalised closing direction is set to the vertex position, and the angle between this vector and the negative normal direction is determined. The closing vector or force is divided into two forces. One force acts in the direction of the negative normal and the other force acts perpendicular to this force. This division can be seen in the lower figure of 3.5 *b*). The larger the angle, the less force is applied to the vertex in negative normal direction. An angle of 90° (case *a*)) would have no component in negative normal direction and an angle of 0° results in a vector with length 1, as the closing vector is normalised. Mathematically this process can be described by trigonometrical formula in case of right-angled triangles:

$$f_{external} = \cos(\alpha) * hypotenuse * (-\vec{n}) * s \quad (3.3)$$

with α representing the angle between the closing vector and negative normal $-\vec{n}$. As the closing vector is normalised, *hypotenuse* is always 1. s is a constant, scaling the strength of the force, otherwise the strength would be in the range between 0 and 1. The value is set to 50 based on testing how realistic the deformation looks.

During the clipping process, only collisions resulting in a deformation are wanted, thus all collisions with an angle larger or equal to 90° are rated as no collisions. Otherwise the clip would collide and is not closed further on, as the vessel is not deforming. Thus, the maximum angle was chosen to be 70° , which results in smaller deformation, but it is still enough to be noticeable.

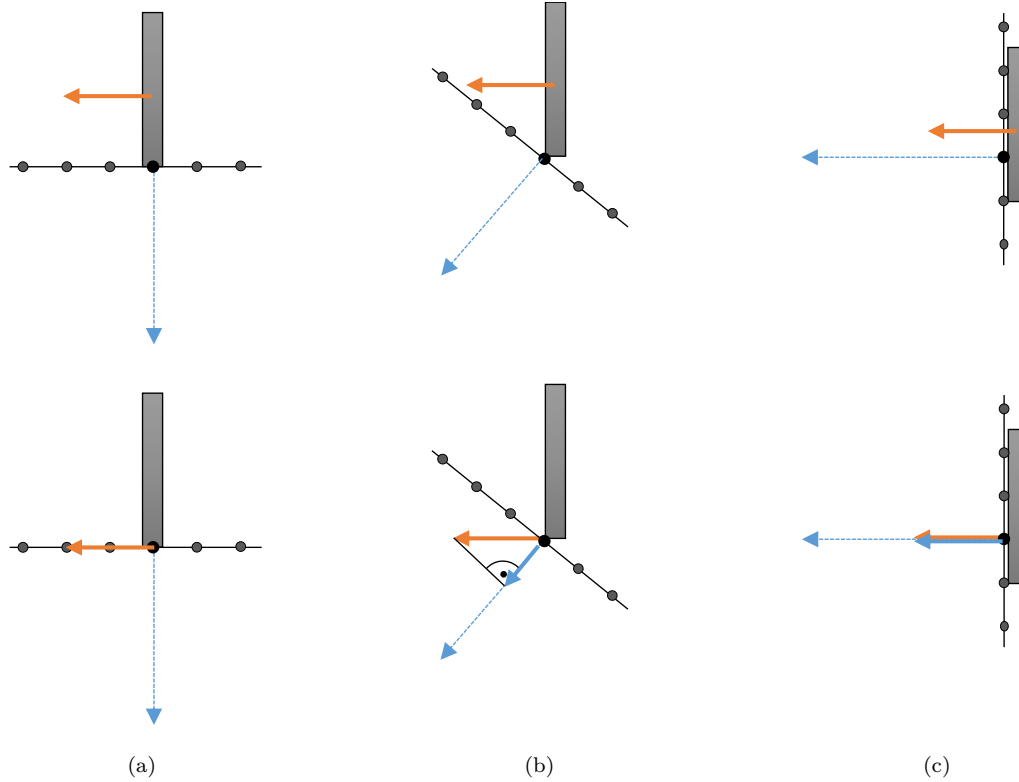


Figure 3.5: Deformation direction based on the normalised closing direction (orange arrow) of the clip and the negative normal direction (dashed blue arrow) of the colliding vertex of the vessel mesh. *a)* Angle between these two directions is too large, so there is no force in negative normal direction applied to the vertex. *b)* Closing vector is divided into two vectors, resulting in the blue force that is applied to the vertex. *c)* Closing direction is parallel to the negative normal, so the complete force is applied to the vertex.

For each vertex or mass point, the total force acting on it is stored. So after colliding, the external force is added to the total force. The next steps describe one iteration of the deformation process.

First, spring forces are determined on basis of the previously mentioned Hooke's law (see Section 2.3). This implies the following formula for spring forces:

$$f_{ij}^t = k_s * \frac{x_j - x_i}{|x_j - x_i|} * (|x_j - x_i| - l_{ij}^0) \quad (3.4)$$

where f_{ij}^t is the spring force of the spring at time step t between mass i and j , with their positions x_i and x_j . k_s is the spring constant of this spring and l_{ij}^0 is the rest-length. The

resulting force is applied equally and oppositely to both points. Thus, the force exerting on mass i is f_{ij}^t and on mass j it is $-f_{ij}^t$. This force is added to the total forces of the respective masses. As mentioned in the concept of this deformation model, additional springs between each mass and its initial position are introduced. These springs only act when the clip is opened and the vessels return to their initial shape. Consequently, the force applied by the spring with a rest-length $l^0 = 0$ between a point i and its original position x_{i_0} is calculated as follows:

$$f_{ii_0}^t = k_{s,backwards} * (x_{i_0} - x_i) \quad (3.5)$$

Vertices moving back to their initial position are set to exactly this position when the distance between the current position and the initial position is smaller than a threshold. Also if there are only few vertices that have not yet reached their initial position, they are set back to their position respectively. Setting back the vertices is done because the more a vertex reaches its initial position, the smaller the spring force. To stop additional calculations the vertices are just set back and the corresponding applied force is set to zero.

After calculating the spring forces, the integration takes place. Hereby the next position of each point is determined by the following formula according to the Verlet integration:

$$x_{t+\Delta t} = x_t + (x_t - x_{t-\Delta t}) * (1 - k_d) + \frac{f(t)}{m} * \Delta t * \Delta t \quad (3.6)$$

where $x_{t-\Delta t}$ is the previous position and k_d is the damping constant.

Displacing the vertices to their new position $x_{t+\Delta t,adapted}$ is only conducted if there is no collision. Accordingly, there are two cases how a vertex is displaced:

$$x_{t+\Delta t,adapted} = \begin{cases} x_t + (x_{t+\Delta t} - x_t) * (d_{collision} * 0.9), & \text{if colliding} \\ x_{t+\Delta t}, & \text{otherwise} \end{cases} \quad (3.7)$$

In the case of a collision, the next position is set to a point directly in front of the collision point by moving it by 0.9 times the collision distance $d_{collision}$. If there is no collision, the next position equals the resulting position of the Verlet integration $x_{t+\Delta t}$.

The last step in the deformation iteration is a compensation step. Due to too large time step, errors in form of single vertices that have been moved strongly in a wrong direction can occur. To avoid these errors, a stretching compensation like Duan et al. [62] proposed was included. In their approach, springs have a maximum stretching, ensuring that the springs can not become longer than a certain length. The current stretching of a spring is computed by:

$$stretching_{ij} = (1 + r_s) * l_{ij}^0 - |x_i - x_j| \quad (3.8)$$

where r_s is the stretch ratio, determining the maximum length a spring can reach. If the result is less than zero, meaning that the spring is stretched too much, both masses are displaced towards each other by half of the stretching. Consequently, one has:

$$\begin{aligned} x_i &= x_i + \frac{1}{2} * stretching_{ij} * \frac{x_i - x_j}{|x_i - x_j|} \\ x_j &= x_j - \frac{1}{2} * stretching_{ij} * \frac{x_i - x_j}{|x_i - x_j|} \end{aligned} \quad (3.9)$$

In this section a few parameters were mentioned. Table 3.1 summarises the parameters and their chosen values, which specify the physical properties of the deformable object. The values were determined based on tests with the aim to achieve a deformation as realistic as possible and with as few errors as possible.

Table 3.1: Overview of all parameters and their values.

Parameter	Value
Spring Constant	0.7
Spring Constant (backwards)	0.3
Damping Constant	0.8
Stretch Ratio	1

In Figure 3.6 the resulting mesh deformation of the above presented formulas can be seen.

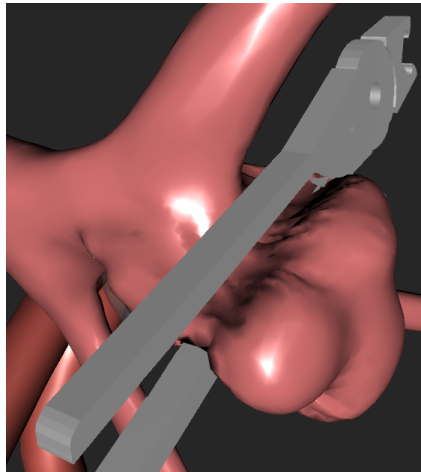


Figure 3.6: Resulting mesh deformation when closing the clip.

3.4 Distance and Tractive Force Feedback

The following section describes the chosen visualisations and their implementation in more detail. There is no division into distance and force visualisations but into the different types of concepts and thus the different implementations.

The distance information for the corresponding visualisations are determined via Unity's `closestPoint`⁶ function. This function returns the point on a collider that is closest to a given position. The position is a vertex on the vessel surface and the collider is the

⁶Unity Technologies, San Francisco: <https://docs.unity3d.com/ScriptReference/Collider.ClosestPoint.html>, date: 24.09.2020

compound collider of the current clip. So for each vertex of the vessel, the closest point on the clip is determined.

The tractive force information is described by the vector between the initial position of each vessel vertex and the current, possibly displaced position. Consequently, the direction and magnitude are available.

3.4.1 Colour Map Visualisations

The basis of the colour maps is a vertex shader. This vertex shader receives information for each vertex via the colour channel. The shader's properties comprise five different colours and thresholds. These properties are set according to the in Section 2.2.3 presented red-green colour scale or the red-blue colour scale, respectively. The red-green scale is set as default and can be changed to the red-blue scale by a toggle in the option list. In Figure 3.7 a) and b) the exact colours, the corresponding thresholds for the distance and force map can be seen. The actual colour of a vertex is then determined by the distance or force value delivered via the colour channel. Here the values are just written to the red channel of the RGB colour values. In the shader, the colour is obtained by linearly interpolating between the colours based on the thresholds and the current distance or force value.

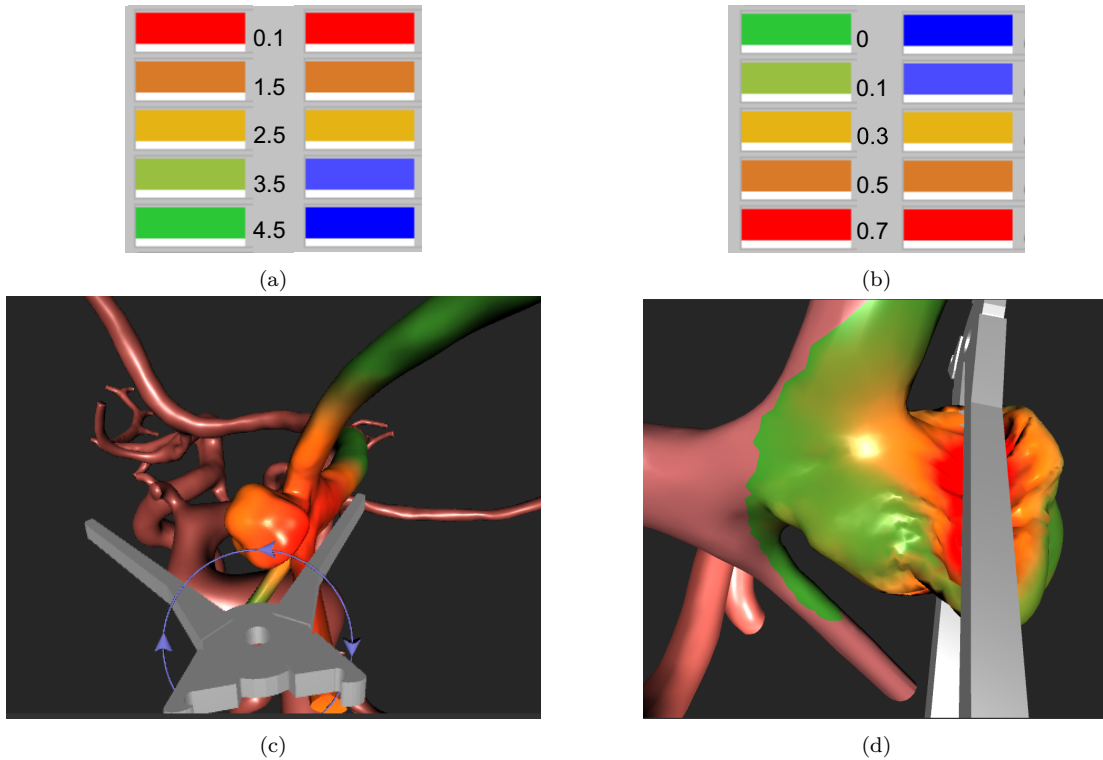


Figure 3.7: (a) and (b) are the underlying colour scales for the distance map and the force map. (c) and (d) depict the distance and force maps in the simulation tool.

3.4.2 Single Object Visualisation

The distance visualisation using a cylinder is the only developed and used single object visualisation concept. This was realised by using a cylindrical model, created in Blender⁷ Version v2.79. This model is constantly set to the currently shortest distance. Not just the orientation and length is adjusted according to the distance, but also the radius. The radius is one quarter of the length. Consequently, not just the length but also the radius convey the shortest distance. For colour-coding the cylinder, here again a vertex shader and the colour scale for distance were used. Figure 3.8 shows the navigation using the distance cylinder.

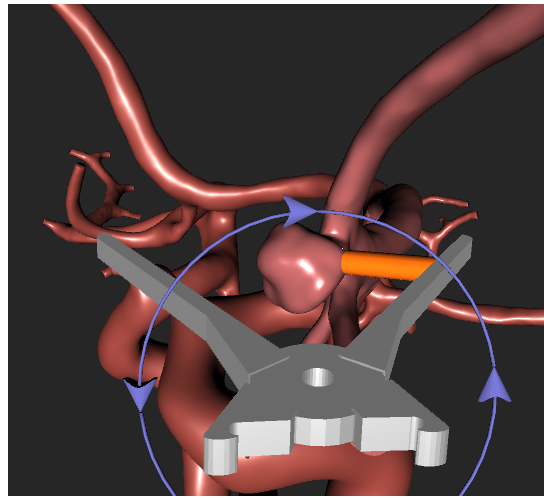


Figure 3.8: Navigation using the cylinder visualisation.

Pseudocode 3.1 shows the update of the cylinder depicting the shortest distance.

```

1 Data:
2 length: the currently smallest distance
3 Line: a tuple, including the start and end position of the line (
      smallest distance)
4
5 cylinder.length = length
6 cylinder.width = length/4
7
8 //set the position to the start point. And the cylinder has to
  look at the end position
9 cylinder.position = Line.item1.position
10 cylinder.LookAt(Line.item2)
11
12 cylinder.colour = GetColourFromDistance()
```

Source Code 3.1: Updating the cylinder data

⁷Blender, Amsterdam: <https://www.blender.org/>, date: 16.09.2020

3.4.3 Multiple Object Visualisation

For coordinating multiple objects in Unity, a `GameObject` is created having a certain amount of children at the beginning. These children are, depending on the visualisation, either rays or glyphs. The number of active objects depends on the number of objects currently required. If there are not enough objects to depict all currently available distances, more object are instantiated. If there are more objects than distances after the completed iteration, unused objects are deactivated. This process is summarised in Pseudocode 3.2, where a drop glyph is updated.

```

1  Data:
2  vertexIdx: the index of the currently displaced vertex
3  countDisplacedVertices: the amount of so far displaced vertices
   in the current iteration
4  objectListDrops: list of all drop glyph objects
5
6  direction = displacedVertices[vertexIdx] - initialVertices[
   vertexIdx]
7
8  if(direction != Vector3.zero)
9      //new children are instantiated, if needed
10     if(countDisplacedVertices > objectListDrops.nCountChildren)
11         objectListDrops.InstantiateChildren()
12     end if
13
14     currentDrop = objectListDrops[countDisplacedVertices]
15
16     //active the object
17     objectListDrops.SetChildActive(currentDrop, true)
18
19     //set the drops values to the current displacement data
20     currentDrop.direction = direction
21     currentDrop.position = displacedVertices[vertexIdx]
22     currentDrop.colour = GetColorFromDisplacement()
23     currentDrop.colour.a = GetTransparencyFromDisplacement()
24     currentDrop.scale.z = GetScaleFromDisplacement()
25 end if

```

Source Code 3.2: Updating a displacmente drop glyph

The rays are implemented by employing Unity's Line Renderer⁸. Each line has a start position, an end position and a colour. The distance rays have a vertex on the vessel surface serving as start point and the nearest point on the clip serving as end position, whereas the force rays have the corresponding initial and current vertex position as end points.

The force rays are rendered fully opaque, while for the distance rays two options for opacity are implemented. The user can either set the transparency value via a slider, having the same value for each ray, or if the transparency is not set, it is graded according

⁸Unity Technologies, San Francisco: <https://docs.unity3d.com/Manual/class-LineRenderer.html>, date: 06.06.2020

to the distance. Both the distance rays with two different opacity values and the force rays can be seen in Figure 3.9.

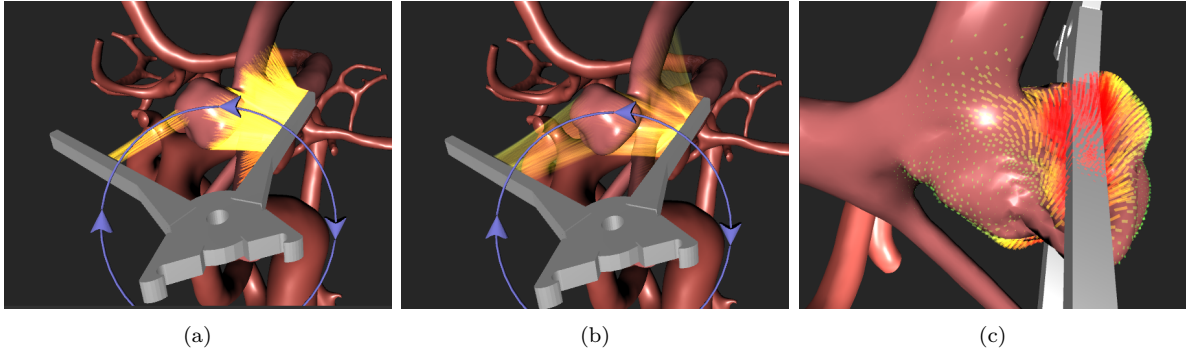


Figure 3.9: Rays used for distance visualisation with different opacity values in (a) and (b) and for tractive force visualisation (c).

As described in Section 2.2.2, the arrow glyphs only convey magnitude and direction by their colour and orientation. The drop glyphs, however, depict the magnitude also by their transparency and length. For both, fix gradations are used. This results in the visualisations shown in Figure 3.10. In addition to the glyph visualisations on their own, the glyphs can be combined with the force colour map. These combinations were also used as further concepts during the evaluation.

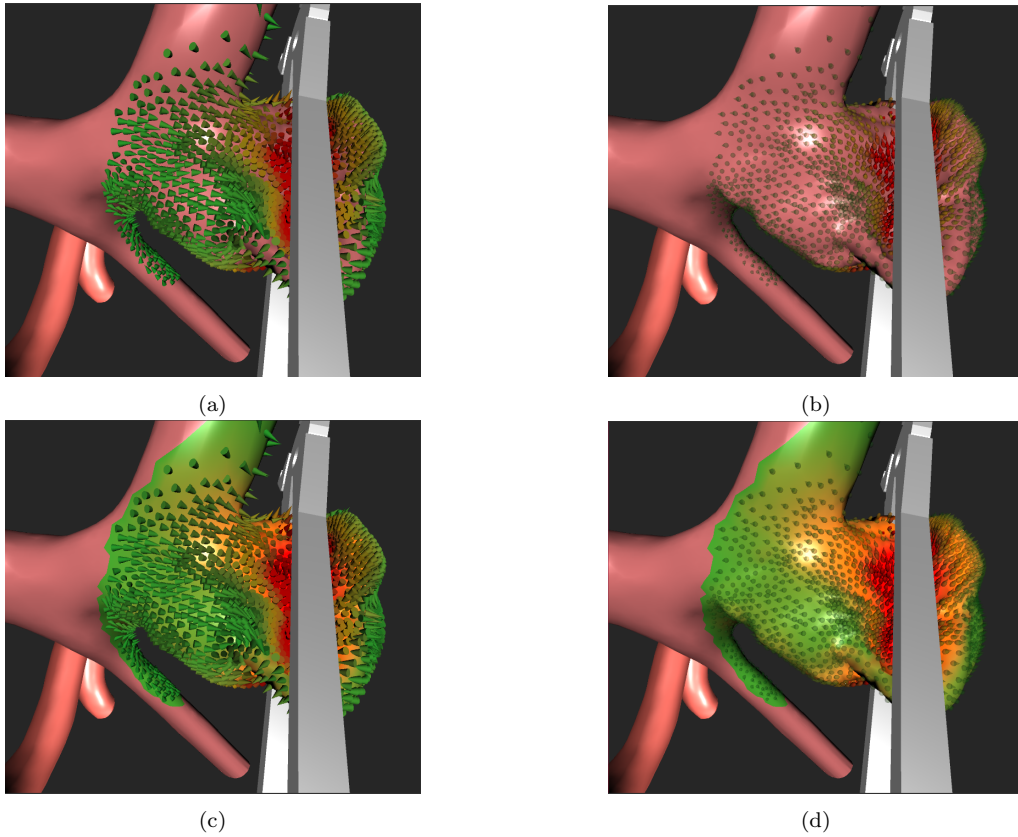


Figure 3.10: Glyph visualisations: (a) arrow glyphs, (b) drop glyphs, (c) combination of arrow glyphs and colour map, (d) combination of drop glyphs and colour map.

4 Evaluation

The following section serves to evaluate the clipping tool and the comprised distance and tractive force visualisation concepts. In addition to the already mentioned feedback meetings with the neurosurgeon during the implementation and at the end of the development, an online survey was performed. After describing the survey, the results of the survey and of the feedback meetings are presented.

4.1 Quantitative Evaluation

For quantitative evaluation of the visualisation concepts an online survey was chosen. The main advantage of an online survey is that it is a fast and easy way to receive feedback. Holding a meeting with several experts is much more time consuming. Furthermore, it is very difficult to arrange meetings with physicians, as they have a tight schedule and spontaneous operations may occur. As the focus is on the visualisations, they are the main part that have to be evaluated. Therefore, it is an appropriate way to evaluate the concepts based on images instead of evaluating them during a meeting that includes directly interacting with the tool.

This survey was forwarded to experts and prospective target audience of such a clipping simulation, meaning neurosurgeons and medical students of the Otto-von-Guericke University and University Hospital Magdeburg. It shall be noted that the students that took part in the survey have previous knowledge in the area of neurosurgery. All of them were familiar with aneurysms and clipping beyond the textbook because of their final assignments or field work in this area. Therefore their answers have a certain relevance. As the survey was only forwarded to local experts, it was conducted in German.

4.1.1 Survey Generation

The online survey was created with the online tool LamaPoll¹, which conforms to the General Data Protection Regulation. Additionally to the following description of the survey, the main part of the survey is added to the appendix.

Before asking questions regarding the visualisations, a short introduction including a description was followed by confirming the data protection ordinance. Afterwards, the following demographic data were collected to get an insight of the people answering the survey:

- Sex: The possible answers were female, male or diverse.
- Age: The age was categorised into different ranges, ranging from 0 to above 80.

¹Lamano GmbH & Co. KG, Berlin: <https://www.lamapoll.de/>, 12.08.2020

- Whether the participant was currently a practising doctor, a medical student or something else. If the participant was a practising doctor, they were asked in which area they are working and for how long.

The question about the participant's experience is important to demonstrate the significance of the results. Gathering the sex and age is not necessary for evaluating the visualisations, nevertheless they were asked for a reason. It could happen that for example all female or young participants favour another concept than male or older participants. To reveal such scenarios, sex and age are asked, however no correlation between one of these data and specific answers could be found.

The first section of the survey referred to visualisation concepts of tractive force. First, each concept is treated separately and evaluated one by one. Therefore, they first are introduced with a short description and the help of two images. Both images show an aneurysm with applied clip, one without any force visualisation, the other with the current visualisation concept. All images showing an applied clip present in the survey are similar concerning the viewing angle, the clip placement and how far the clip is closed. Based on the two images, the participants have to rate seven statements with the commonly used Likert scale [73]. Rating with one implies that the participant strongly agrees, five that they do not agree. The following statements were given for each visualisation concept:

- The visualisation is intuitive.
- The visualisation provides additional information.
- The visualisation creates added value.
- The vessels and relevant information are not occluded.
- You [the participant] can easily locate regions with strong tractive force.
- You [the participant] can recognize in which direction the surface is dragged.
- You [the participant] can imagine using this visualisation in a corresponding tool.

These statements aim to cover the requirements defined in Section 2.7. Thus, there are statements revealing whether the visualisation is intuitive and whether relevant information is occluded. Providing additional information and added value are separated into two statements, as additional information such as distance information could be provided in a way without creating added value in terms of supporting navigation. The additional information is specified by two statements regarding the regions with strong force and direction. Asking whether the participant would use such a visualisation aims to get an insight whether they not just like a visualisation but also would use it.

After evaluating the single concepts, the participants have to state whether they prefer a combination of glyphs and colour maps or just the glyphs. This is done for both glyph types separately by showing an image on which just the glyphs are used and an image of the glyphs combined with the map.

To complete the force section, the participants have to create a rank of the presented force visualisations. This serves as a direct comparison of all concepts. Afterwards the participants have the possibility to leave a comment regarding the tractive force concepts.

The second section deals with the distance visualisations. As they serve to improve navigation and understanding of spatial relations, short video clips were incorporated in the survey. After describing the current distance concept, two videos were previously recorded and shown, both showing a forward movement of the clip in direction to the aneurysm starting from the hole in the skull. Here again one video is without any visualisation and the other one uses the current visualisation. To not falsify any results, in all videos the same movements and angles are used. Otherwise, different angles could have led to a better or worse presentation of the different concepts, resulting in the outcomes not being comparable. The participants have to select if they prefer the navigation with or without the current visualisation. Afterwards, they again have to rate seven statements, covering the defined requirements for the visualisations:

- The visualisation is intuitive.
- The visualisation provides additional information.
- In your [the participant's] opinion the visualisation supports the navigation.
- The visualisation provides a better understanding of spatial relations and distances.
- Relevant vessels and information are not occluded.
- You [the participant] can easily detect near regions.
- You [the participant] can imagine using this visualisation in a corresponding tool.

Instead of asking whether the visualisation creates added value, the added value of distance visualisations was specified by asking whether they think the visualisation supports the navigation. The statement about spatial relations and distances should reveal the added value, too.

This section also ends with a ranking of the presented distance visualisations and the possibility to write a comment.

4.1.2 Results of the Survey

The survey was conducted by eleven people in total. Four of them are practicing neurosurgeons, the others are medical students with an appropriate background as mentioned before. Two of the neurosurgeons have one to five years of experience, the other two have six to ten years of experience.

Aside from three students, who were younger, all other participants assign their age in the category 25 to 39 years.

To reveal and compare the results, the average scoring for each visualisation and statement was determined. The average is prone to outliers, however it was chosen as comparison, as the values range from 0 to 5 and thus no extreme outliers are possible. In addition, the average is more precise than the median and enables a more detailed comparison. Supplementary, the standard deviation was calculated to reveal the spread, meaning the average deviation from the mean. Consequently, the standard deviation is a measure, showing how strongly the opinions of the participants coincide.

In Figure 4.1 the average scoring for each distance concept is displayed. It can be seen that the distance map has the highest score in all categories except for the one regarding occlusion. The difference between the assessment of the rays and cylinder is not as high as between them and the map. The statement about the occlusion and that near regions can be detected easily aside, the rays perform a bit better than the cylinder. High standard deviations concerning the results of the rays and cylinder demonstrate the very different opinions about these concepts.

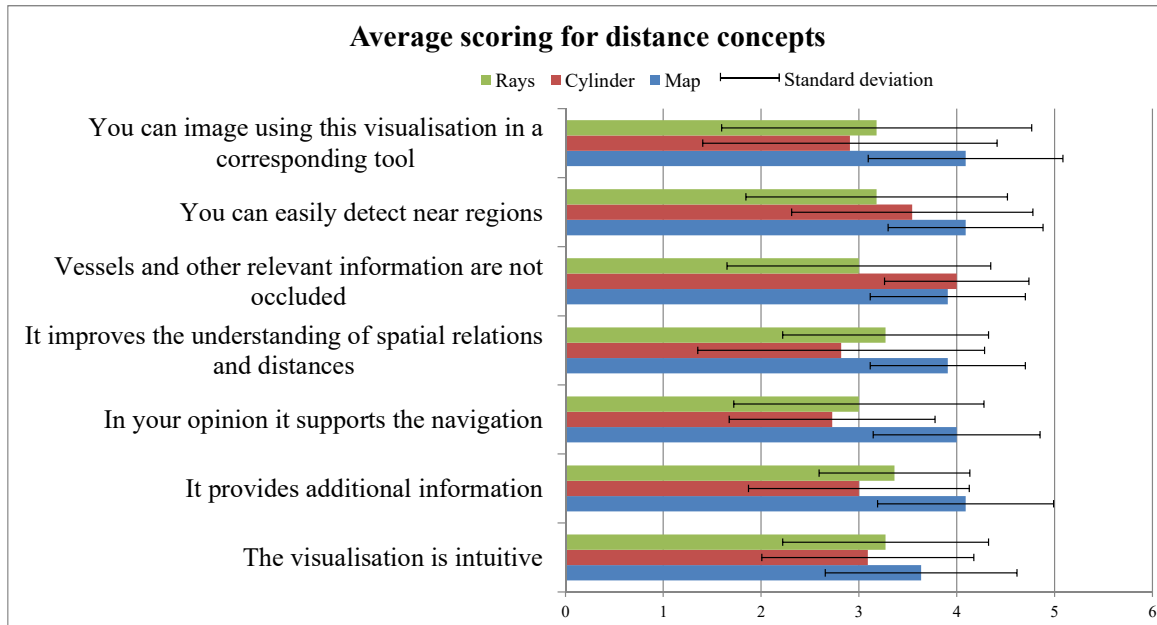


Figure 4.1: Average scoring for the different distance concepts regarding the different statements and the corresponding standard deviation.

Regarding the distance map, around 64% of the participants prefer the navigation with the distance map over navigating without any visualisation. For the cylinder and rays the value is lower, 36% and 45% respectively. Nevertheless, the participants rated the cylinder better than the rays in the overall ranking. The results of the rankings are visualised in Figure 4.2. The distinct favourite in this comparison is the distance map.

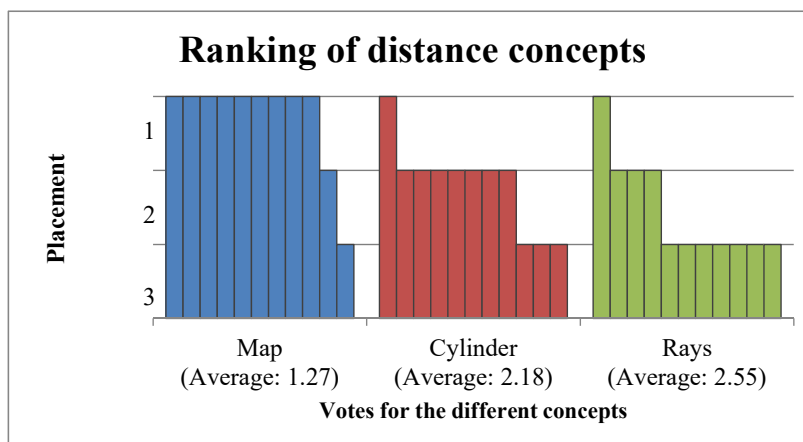


Figure 4.2: Ranking of the different distance concepts. Each bar represents a chosen rank by a participant for the specific concept.

At the end of the section about the distance visualisations the participants were encouraged to write an additional comment concerning improvement proposal or to reason their rating. One participant stated the following:

You can no longer see the cylinder from a certain angle. The clip would have to be transparent in order to be able to see better. The rays occlude far too much.

After completing the presentation of the results concerning distance visualisations, the results of the survey regarding tractive force visualisations are presented. Figure 4.3 reveals the average results of the scoring for the tractive force concepts and their standard deviations. Here, as well as for the distance feedbacks, the colour map gains the highest score for each statement. The results of the rays and drops are often nearly the same, except for the statement regarding occlusion and the statement regarding direction. In spite of that, the participants would rather use the rays than the drops in a corresponding tool.

Comparing the two types of glyphs, the arrows are only rated better than the drops in terms of visualising the direction and come last place in all other categories. Nevertheless, the participants slightly prefer the arrows.

In most categories the map and rays have smaller standard deviations than the two glyph-based concepts, indicating a smaller spread of the scores.

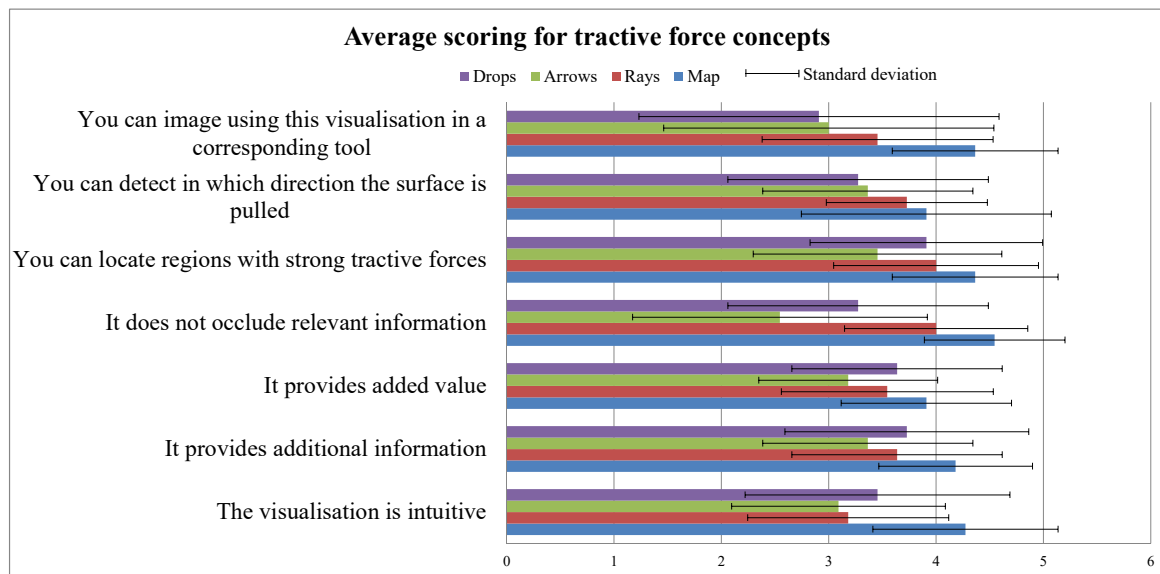


Figure 4.3: Average scoring for the different tractive force concepts regarding the different statements and the corresponding standard deviation.

Before comparing all force visualisations by ranking them, the combinations of colour map and arrow glyphs as well as drop glyphs were introduced. In both cases, the combination was preferred over the visualisations with just the glyphs. In case of the arrow glyphs, 73% of the participants favour the combination and in case of the drop glyphs all participants chose the combination.

The popularity of the map, which is evident in the above statements, is reflected in the results of the ranking, which is shown in Figure 4.4. Also, both glyph and map combinations are rated well. The different placements of the rays are nearly equally distributed on all placements, whereas the two glyph-based visualisations are mainly distributed on the middle and lower placements. This results in the drops having the lowest average placement with 4.72.

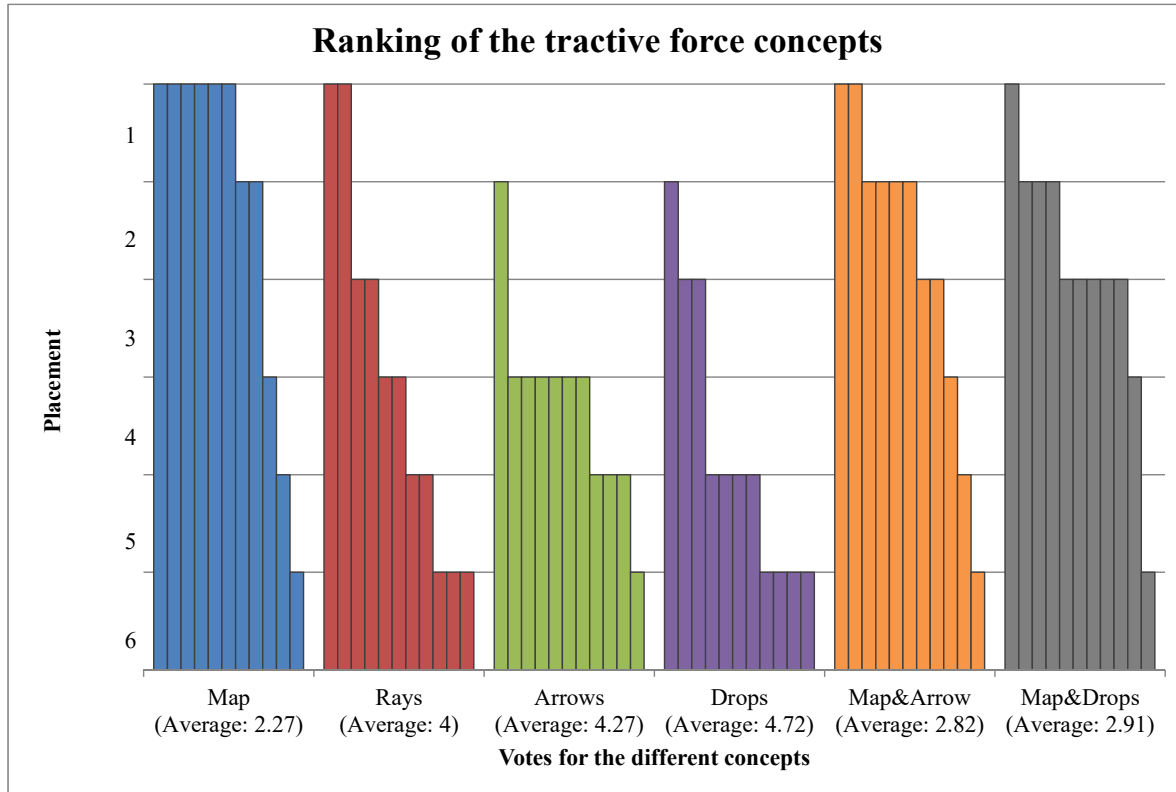


Figure 4.4: Ranking of the different tractive force concepts. Each bar represents a chosen rank by a participant for the specific concept.

As before, the participants could leave a comment related to the tractive force visualisation concepts. The following was remarked by a participant:

In my opinion, most variants occlude the vessels too much. Therefore, I think the colour map is the best.

4.2 Qualitative Evaluation

As final evaluation, the think-aloud method was used. Here, people are asked to think aloud while solving a problem or testing a product [74, 75]. This open evaluation was chosen as a contrast to the strict survey. Open feedback, unrestricted by a survey's specific phrasing, regarding the visualisations can be more helpful to get an insight why potential users rated something as good or bad. Additionally, the overall usability of the tool can be assessed, as the participants of the survey only get impressions of the tool and they have never seen the tool as a whole or interacted with it. Nevertheless, the focus of this work is on the visualisations and not on developing just a user-friendly tool. That is why the

focus of the evaluation is on the visualisations, especially on the distance visualisations. The participants of the survey are only provided with videos but they do not navigate the clip by themselves. So the real situation of navigating in the tool was not given. In contrast to this, the neurosurgeon of the qualitative evaluation navigated the clip on his own. Because of this he could evaluate the distance visualisations much better.

For this evaluation, a meeting with a neurosurgeon with four years of experience in the field of neurosurgery and clipping was held. First, he was given a short overview of the tool. Then it was his task to interact with the clip and camera to get familiar with the control. While doing this, he was asked to try out the different distance visualisations and encouraged to comment on the force visualisations when he closed the clip.

During the evaluation process, one person other than the surgeon and the author of the thesis was present. The author was presenting the tool, asking questions and sometimes requesting the surgeon to comment on something. The other person was writing the protocol. The comments of the neurosurgeon are integrated in the discussion of the next section.

4.3 Discussion

Within the discussion, first the chosen evaluation methods are assessed for their appropriateness and their drawbacks are revealed. Then the results of the distance and tractive force visualisation concepts are discussed, and finally the tool is evaluated as a whole.

4.3.1 Choice of Evaluation Methods

A survey is a good and fast way to obtain different opinions, but there are limitations. Limitations of the chosen evaluation methods and some suggestions for improvement are presented in the following. For example, it is not possible to evaluate the whole tool and its usability within a survey. That is why the survey just focuses on the evaluation of the different visualisation concepts. This is mainly done by comparing the visualisations based on different aspects and ranking them. But sometimes it is helpful to get more in-depth information about the participants' choice. One could for example ask whether glyph A is better than glyph B because of its design or whether the different exploited visual variables are the reason. Comparing the glyphs, it would have been better to first use the drops just like the arrows, without mapping the magnitude to size and transparency. Thus, the designs would have been compared directly. In a next step the additional visual variables size and transparency should have been added to both glyphs. By separating the design from the selection of visual variables, the reasons for preferring one of them would have been much more obvious.

Generally, knowing the exact reasoning that motivated the concepts' rating would have enabled a more differentiated evaluation. This way, reasons could be separated into those who are fundamental and those who are more detailed. It should be distinct for example whether a concept is generally an inappropriate visualisation or whether it is just the choice of color, size or transparency, which can be changed easily. Accordingly, the concepts do not have to be discarded, but could be adapted and improved.

As already mentioned in the results, one participant mentioned that most visualisations

occlude the vessels. This is an important point and was also one of the evaluation criteria. But the transparency of distance rays for example can be changed by the users themselves, which was not mentioned in the survey and thus not considered.

Another important issue are the distance visualisations, which were rated based on similar and thus comparable videos. Here it would have been interesting whether the participants think they can navigate without a distance visualisation and thus do not need any additional support. If so, it would be interesting whether they still have the same opinion after navigating on their own. Sometimes there is a big difference between what the users think they can do and what they can actually do. Thus, letting the user navigate on their own would have been a better and more meaningful evaluation of distance visualisations. This could have been done by creating a short web-based application with just an aneurysm and clip to navigate. Hereby, the navigation has to be the same as in the tool, which means the clip has to be navigated via keyboard. Another option would be to hold meetings with more neurosurgeons than the one that was done.

4.3.2 Distance Visualisations

In this part, the distance visualisation concepts are discussed based on the requirements presented in Section 2.7.

As mentioned in the discussion of the evaluation methods, the validity of the results regarding distance visualisations obtained in the survey have to be reconsidered. The described apprehension concerning the difference between just seeing the navigation videos and navigating yourself was confirmed during the qualitative evaluation. It quickly became obvious that it is not easy to estimate the distances and spatial relations as the neurosurgeon closed the clip several times when the clip was still in front of the vessels. He quickly realised that the distance visualisations are necessary and a big support for navigating the clip, despite previously stating that he considered the distance visualisations redundant when just seeing them without interacting with the tool. In other words, he thought the distance visualisations are unnecessary, but recognised their usefulness while navigating. Based on this discovery, the significance of the survey's results should only be considered cautiously. Therefore, the visualisation concepts' usefulness was determined predominantly based on the qualitative evaluation.

The visualisation concept that is occluding the vessels the most is the ray visualisation. Nevertheless, this was rated as suitable by the neurosurgeon, as the transparency can be regulated by the user. Among all the visualisation concepts the rays were the only one that provided the neurosurgeon with sufficient support to navigate the clip. The map shows the distances as values, but it does not draw the corresponding lines and thus points on the clip. The cylinder shows the line, but only for the smallest distance. The main drawback of this concept, the fact that the cylinder is not always visible, was already noticed by a participant of the survey. Some rays may also not be visible, but the user still can see the rays of the surroundings.

An overview of how strongly the individual concepts meet the requirements can be seen in Table 4.1. The one neutral grading of the rays is compensated by the added value that is not provided with the other visualisations and by the possibility to adapt the transparency individually.

Table 4.1: Overview of how strongly the concepts meet the requirements.

Requirements	Map	Cylinder	Rays
Prevent occlusions: The visualisation should not occlude important information. The vessels always should be visible, so the user can still observe the course of vessel and their shape.	+	0	0
Unobtrusive: The visualisation should not hamper the user. Therefore, the feedback always should be unobtrusive, so the main focus is still on the vessel and clip. Appropriate interactions with the device, meaning the navigation and closure of the clip, and completing the task should always be possible.	+	+	+
Added value: The visualisation should create added value. In terms of distance information this means facilitating the navigation of the clip. This includes that the feedback is always available and correct.	-	-	+
Intuitive: The visualisation should be intuitive and easy to understand, so no learning is required. This refers to each visualisation concept as a whole, but also to the underlying colour scale.	+	+	+

4.3.3 Tractive Force Visualisations

In all categories of the survey, the map achieves the highest scores and it was the absolute favorite of the neurosurgeon. This concept is not as complicated as the glyph-based concepts, nothing is occluded and it provides the user with enough information. Although the map is the only concept that does not visualise the direction of the force, the neurosurgeon emphasised that this is still enough information. The direction is not really important because it can be derived from the vessel deformation. The neurosurgeon as well as one participant underlined that all other visualisations occlude the vessels. Additionally, the surgeon mentioned that in his opinion the map is the most visually pleasing concept.

The resulting assessment of the individual tractive force concepts in Table 4.2 is composed of the results of the survey combined with the feedback of the neurosurgeon. The evaluation of the first requirement, preventing occlusions, results from the statement in the survey concerning occlusion. The second requirement, being unobtrusive, is evaluated mainly based on the neurosurgeon's association. Due to this association, he stated that the drops seem out of place on an anatomical structure. Concerning the added value, the following statements of the survey were included:

- The visualisation provides additional information.
- The visualisation creates added value.

- You [the participant] can easily locate regions with strong tractive force.
- You [the participant] can recognize in which direction the surface is dragged.
- You [the participant] can imagine using this visualisation in a corresponding tool.

The last requirement was directly asked in the survey.

Table 4.2: Overview how strongly the individual concepts meet the requirements.

Requirements	Map	Rays	Arrows	Drops
Prevent occlusions: The visualisation should not occlude important information. The vessels always should be visible, so the user can still observe the course of vessel and their shape.	++	+	- -	-
Unobtrusive: The visualisation should not hamper the user. Therefore, the feedback always should be unobtrusive, so the main focus is still on the vessel and clip. Appropriate interactions with the device, meaning the navigation and closure of the clip, and completing the task should always be possible.	++	+	-	-
Added value: The visualisation should create added value. Regarding the tractive force feedback regions with high force should be highlighted and clearly visible.	++	+	0	0
Intuitive: The visualisation should be intuitive and easy to understand, so no learning is required. This refers to each visualisation concept as a whole, but also to the underlying colour scale.	++	0	-	-

In summary, it can be said, that the colour map is the best concept, providing the user with an appropriate additional force information. As the neurosurgeon stated, this visualisation is a good compensation for the lack of haptic feedback.

4.3.4 Clipping Simulation Tool

In addition to the requirements regarding the visualisations, a few requirements for the tool in general. These requirements are now evaluated individually.

The first four requirements refer to the different scenes that should be comprised in the tool. All four scenes, the aneurysm selection, craniotomy, clipping and comparison scene

are available. Here, the user can accomplish the respective tasks, including selecting an appropriate aneurysm, cutting an adjustable hole, navigating and applying multiple and different clips, and comparing two saved clipping results. The next, non-functional requirements of the tool were evaluated during the qualitative evaluation with the neurosurgeon.

The first non-functional requirement is having an appropriate performance. The most critical situation within the workflow regarding the performance is during the closure of the clip and thus calculating the mesh deformation. Depending on the computer on which the tool is running, there are performance problems during this step. They manifest as stuttering camera motion. For the evaluation with the neurosurgeon a laptop with the following technical data was used:

Computer 1:

- Processor: intel core i7-7820HK CUP 2.9GHz, 2901 MHz, 4 cores, 8 logical processors
- Working memory: 16GB
- Graphics card: NVIDIA GeForce GTx 1080 with Max-Q Design

Using this computer, there were no problems regarding the performance, whereas on a computer with the following properties, the camera movement during clipping is judery:

Computer 2:

- Processor: intel core i7-4510U CUP 2.0GHz, 2601 MHz, 2 cores, 4 logical processors
- Working memory: 12GB
- Graphics card: NVIDIA GeForce GTX 850M

The performance on both computers was compared by calculating the frames per seconds (*fps*) during navigating, clipping, meaning deforming, and after clipping. After clipping means the clip is opened again after deforming the vessels. Consequently, the mesh is still changing, but there is no external force applied to the vertices. As the clip is near the vessels, the volume of interest around the clip contains vertices, for which ray casting is performed. The measured values can be seen in Table 4.3 below. Computer 1 refers to the more powerful computer, used for the evaluation whereas computer 2 refers to the computer used for the development.

Table 4.3: Overview of the measured frames per seconds during three different situations. Computer 1 is the more powerful computer, used for evaluating, than computer 2.

Situation	Computer 1	Computer 2
Navigating	36 <i>fps</i>	30 <i>fps</i>
Clipping and deforming	12 <i>fps</i>	5 <i>fps</i>
After clipping	22 <i>fps</i>	16 <i>fps</i>

This recognisable drop of frame rate during the closure of the clip can be tolerated, as the user does not navigate the clip in this phase and as in this process, camera movements are not as important as during navigation. The result can be saved and inspected in the comparison scene where no deformation, ray casting or any other expensive calculations are reducing the frame rate. During the qualitative evaluation with the neurosurgeon, he did not notice any judder or delayed reactions.

The next non-functional requirement refers to realism. The Circle of Willis is a segmented object based on real computed tomography data. As this patient is a healthy person and the aneurysms were additionally modelled, the aneurysms are no real cases. But they are realistic, as they were modelled based on the knowledge and instructions of the neurosurgeon. Thereby, only cases for which clipping would be the probably treatment of choice were modelled.

Besides the aneurysm models, the clips were also modelled within the scope of this thesis. As they were constructed with the help of a real product catalogue and the selection of the neurosurgeon, they can be rated as realistic enough for such a simulation. The most important sizes, like the jaw opening and length are satisfied. Nevertheless, not all sizes were given by the product catalogue and they were not modelled by a professional or experienced person, resulting in small deviations. To be closer to reality, they should be constructed by a professional designer of the corresponding clip company.

During craniotomy the neurosurgeon remarked that cutting the hole looks good, but could be more realistic by not cutting a circular hole but a hole that is a bit more heart-shaped, as this is done in a real craniotomy. Furthermore, the skull and vessels in both scenes, the craniotomy and clipping scene are rotated in the wrong way. They are oriented like a person looking at the user. But in a surgery, the patient lies on the table and the head is a bit rotated, so the surgeon is facing the side of the skull. This can easily be implemented, orienting the skull and internal vessels in the right way as a default setting.

During clipping, the surgeon stated that the deformation of the vessels and aneurysms are realistic enough for this simulation. He especially liked the ‘pulsation’ resulting from the displacement calculations and different forces acting on the vertices. According to him, the ‘pulsation’ improves the realistic impression of blood vessels.

Although he liked the control via keyboard and mouse, he suggested to think about implementing such a tool in a virtual reality environment and with a pen-like device for interacting. This could increase the realism in future simulations.

To increase the realism of the whole workflow, he recommended to add a pre-clipping scene or evaluation. Usually after applying the clip in a real surgery, the surgeon has to check whether the aneurysm is neutralised and whether the surrounding vessels are still open. Neutralising the aneurysm means that no blood is flowing into the aneurysm anymore. Possible ways to implement this are presented in the next Section (5.3).

The last non-functional requirement is the usability. The neurosurgeon emphasised that the tool as a whole looks inviting and the user has a good overview of the issue. The main focus of the usability was on the interaction with the tool during the clipping procedure. Regarding the interaction with the clip, the neurosurgeon stated that he likes the interaction via keyboard. Thereby, the green auxiliary line that was implemented, showing the current axis along which the clip is moved was rated as very helpful. One drawback of this control is that the clip can only be moved along the fixed three axes. So if the user wants to move the clip diagonally to the axes, they have to press two keys alternately. That is why the neurosurgeon would prefer the possibility of changing the axis, meaning

the green auxiliary line. Therefore, having the auxiliary lines as a handle would probably be a better way of interaction in order to determine the direction along which the clip is moved. Then only the keys ‘E’ and ‘Q’ are needed to move forward and backward on the chosen line. Determining the direction via camera, like it is done in first person video games, is not an option, as in a real clipping surgery the surgeon has a fixed field of view and as the clip is moved freely and independently of the viewing direction.

Besides translating the clip the neurosurgeon also liked the rotation via the one handle and especially just moving the mouse and pressing left button. The other mouse interactions to steer the camera were also rated as appropriate.

Closing and opening the clip via the down and up keys is a suitable way. Here he commented that it is also necessary to not just close the clip partially but also to open it again partially. In the tool the opening was implemented as a complete opening when pressing the key, but in a real surgery it is common to partially reopen and adjust the clip. This can easily be implemented just like the closing procedure.

When changing the current clip, the neurosurgeon liked the selection of clips, but instead of a drop down menu with the technical properties of the clips he would prefer images of the clips. So instead of a drop down menu the clip selection should be implemented similar to an inventory where the user can see images of the clips.

Table 4.4 summarises the requirements and the extend to which they are met.

Table 4.4: Overview of requirements for the simulation tool and the extend to which they are met.

Requirement		Is the requirement met?	Explanation
Aneurysm Selection Scene		fulfilled	A selection scene to choose one of the predefined aneurysms is available.
Craniotomy Scene		fulfilled	The user can select an appropriate place and size of a round craniotomy hole.
Clipping Scene		fulfilled	In the clipping scene, the user can navigate a selected clip, close and open the clip and can apply multiple and also different clips.
Comparison Scene		fulfilled	In the comparison scene, two saved clipping results can be opened on a split screen and can be compare with the help of tractive force visualisations.
Performance		predominantly fulfilled	The performance of the tool running on a standard PC is not good enough to enable smooth camera movements while closing the clip and deforming the vessels.
Realism		fulfilled	According to the expert, the deformation is sufficiently realistic for such a simulation tool. Furthermore, the modelled clips and aneurysms are based on real data or the expert’s knowledge.

Requirement	Is the requirement met?	Explanation
Usability	predominantly fulfilled	The interaction with the clip via keyboard was rated as appropriate, but could be improved by a modifiable axis. The neurosurgeon stated that tasks and workflow is clear, but here as well, it could be improved by an additional evaluation scene for the clipping result. Consequently, the satisfaction is not completely fulfilled. With the help of the visualisations, an efficient and effective interaction with the simulation tool is ensured.

5 Conclusion

In this last section, the initial question about distance and tractive force visualisations in aneurysm clipping simulations will be answered with the help of the results obtained by the survey and qualitative evaluation. Furthermore, limitations as well as future work are emphasised.

5.1 Summary

Within this master thesis, a clipping simulation tool for unruptured cerebral aneurysms was developed. For this purpose, different clip models were constructed and aneurysm models were carefully selected and modelled. The user can apply various clips on clinical relevant aneurysms. The procedure comprises a craniotomy, moving clips to the aneurysm and applying them. To provide a realistic simulation, the vessels deform based on a mass spring model when the clip is closed. Additionally, the tool provides the possibility to save and compare different clipping results.

This surrounding served as a basis for developing and evaluating different visualisation concepts. The visualisation concepts can be divided in concepts visualising distance information and concepts visualising tractive force information. Regarding both types of information, the aim is to provide added value and not occlude important information or disturb the user.

The developed distance concepts are a colour map, a size and radius adjusting cylinder showing the smallest distance, and semi-transparent rays showing all distances smaller than a threshold. For depicting the tractive force, a colour map highlighting the magnitude, colour-coded rays showing the displacement, and two glyph-based visualisations depicting the magnitude and direction were introduced.

These visualisation concepts were evaluated by experts and prospective target audience via an online survey and by a qualitative assessment with one neurosurgeon. One important finding concerning the distance visualisations is that they are necessary and helpful, although they did not convince the participants of the survey. However, the evaluation with the neurosurgeon revealed that watching videos in a survey and navigating the clip by oneself are totally different circumstances. According to the surgeon, the ray visualisation concept is the most useful distance concept.

The results of the force visualisation concepts of the survey and the surgeon's opinion coincided. Here, the colour map stood out as the best support. Except two neutral people, all participants agreed or totally agreed that they would use this visualisation concept in such a simulation tool.

5.2 Résumé

In both, the visualisation concepts for distance as well as for tractive force, some concepts became apparent to be very useful and prove to be additional support in a clipping simulation. The concepts that did not convince can be helpful to develop new or to refine the suitable concepts, as they reveal the experts priorities and requirements.

However, the appropriate concepts providing added value such as the distance rays and tractive force colour map can already be integrated in clipping simulations for unruptured cerebral aneurysms. Moreover, they can also serve as a basis for visualisations in other similar applications. Another application would be a simulation for surgical treatment of brain tumors. In this case the distance visualisation could also serve as support.

Consequently, the two visualisations enhance a clipping simulation and thus improve a possible training environment for neurosurgeons and trainees.

5.3 Future Work

During development and implementation, several ideas and improvements emerged that could be realised in future work.

Physics Although the neurosurgeon said that the deformation is realistic enough for such a clipping simulation, the deformation can be improved and refined. The whole deformation process could be improved by using a more exact model, for example a volume preserving model. Not just the deformation itself but also the performance could be improved to ensure further distribution and accessibility. Additionally, some properties like ripping of the vessels for simulating an intraoperative rupture could be included. However, this would require more physical properties of blood vessels like wall thickness, pressure and other factors like calcifications. Calcifications could be simulated in the existing model by using different spring constants instead of a uniform value. Thus, specific regions can be more rigid than others.

Workflow and further components To improve the whole workflow, a scene for exposing the aneurysm could be included after the craniotomy. For realising this, tissue deformation and appropriate surgical instruments have to be included. This would comprise brain tissue with the Sylvian fissure which can be opened via medical instruments. After the clipping scene an evaluation scene where the user can check whether the aneurysm is closed completely and the other vessels are not impaired would complete the tool. This could for example be done with a blood flow simulation. It should be no problem to visualise the blood flow the difficulty lies in obtaining the flow data. Via computational fluid dynamics this can be done by several methods, but they all are time-consuming and have to be integrated into the tool.

Another way to check whether the vessels are not impaired by the clipping is to use the centerline and radius instead of a blood flow simulation. With this information after deforming the vessels, the opening of the vessels after clipping can be compared with the opening before deformation. This way it can be checked whether the vessels remain open to blood flow. The centerline and radius can be calculated once for the unit Circle

of Willis and imported with the model or calculated in unity. This could be done once by casting rays from the vessel surface to the inside in negative normal direction and approximating the centerline by the intersection of different rays. Thereby, the radius is also obtained. This centerline can then be used to estimate the opening of vessels by calculating the area of the cross section. As demonstrated in Figure 5.1, the centerline can serve to cast orthogonal rays to the vessel wall. By casting these rays, the area can be approximated.

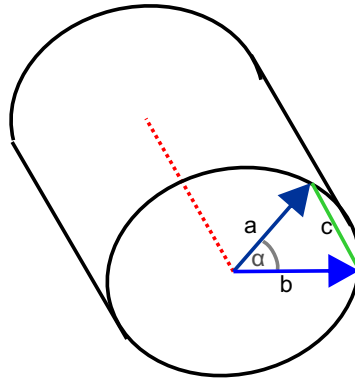


Figure 5.1: Estimation of the cross section area of a vessel.

The smaller the angle α between the rays, the more exact the resulting area of the cross section.

The whole process of checking the extent, to which vessels and the aneurysm are open, depends on the deformation algorithm and closing of the clip. But the neurosurgeon stated that an approximation of the extent to which a vessel is closed in percentage is sufficient. Such an evaluation would be helpful to assess whether the aneurysm is well excluded while the natural blood flow is preserved.

User Interaction The next ideas for improvement relates to the user interaction and devices. The big advantage in terms of availability of a desktop application with keyboard and mouse interactions compensates the disadvantage of not being as realistic as other interaction methods. But as mentioned by the neurosurgeon, the interaction with keyboard could be improved by implementing the axis line as a handle. This way, the user can freely set the axis along which they want to move the clip. Another interaction would be to use a haptic device. By this, the movement of a real medical device is reconstructed more realistically. Additionally, haptic feedback is given when colliding with different tissues. Both would create a much more realistic interaction. Furthermore, a virtual reality environment can be used, also leading to a better immersion. Here, the interaction by moving the hand instead of pressing keys is also more realistic.

Visualisations As described previously, the transparency of the distance rays can be set via a slider. If the user does not want to set a unified value, the transparency is graded linearly based on the distance values. To emphasise small distances, a logarithmic scale could be used, resulting in a stronger descent of transparency with increasing distance. Furthermore, the appropriate visualisation concepts can be refined by for example adding and evaluating different color scales.

Evaluation As mentioned in the evaluation, the validity of the opinions regarding the distance visualisations that were obtained by the survey are doubtful. Consequently, the evaluation of the distance visualisations is only based on the opinion of one neurosurgeon. To get a more representative result, these visualisation concepts should be assessed by more experts.

References

- [1] Monique Vlak, Ale Algra, Raya Brandenburg, and Gabriël Rinkel. “Prevalence of unruptured intracranial aneurysms, with emphasis on sex, age, comorbidity, country, and time period: A systematic review and meta-analysis”. In: *Lancet neurology* 10 (July 2011), pp. 626–36. DOI: 10.1016/S1474-4422(11)70109-0.
- [2] Robert Brown and Joseph Broderick. “Unruptured intracranial aneurysms: Epidemiology, natural history, management options, and familial screening”. In: *Lancet neurology* 13 (Apr. 2014), pp. 393–404. DOI: 10.1016/S1474-4422(14)70015-8.
- [3] Annemijn M. Algra, Antti Lindgren, Mervyn D.I. Vergouwen, Jacoba P. Greving, Irene C. van der Schaaf, Tristan P.C. van Doormaal, and Gabriel J.E. Rinkel. “Procedural Clinical Complications, Case-Fatality Risks, and Risk Factors in Endovascular and Neurosurgical Treatment of Unruptured Intracranial Aneurysms A Systematic Review and Meta-analysis”. In: *JAMA Neurol* 76 (Mar. 2019), pp. 282–293. DOI: <https://doi.org/10.1001/jamaneurol.2018.4165>.
- [4] George Wong, Hai-Bin Tan, Marco Kwan, Rebecca Ng, Simon Yu, Xian-Lun Zhu, and Wai Poon. “Evolution of intracranial aneurysm treatment: From Hunterian ligation to the flow diverter”. In: *Surgical Practice* 15 (Jan. 2011), pp. 16–20. DOI: 10.1111/j.1744-1633.2010.00534.x.
- [5] Fusao Ikawa. “Surgery of Middle Cerebral Artery (MCA) Aneurysm”. In: *Neurovascular Surgery : Surgical Approaches for Neurovascular Diseases*. Ed. by Julius July and Eka J. Wahjoepramono. Singapore: Springer Singapore, 2019, pp. 125–134. ISBN: 978-981-10-8950-3. DOI: 10.1007/978-981-10-8950-3_15. URL: https://doi.org/10.1007/978-981-10-8950-3_15.
- [6] Mayfield Brain & Spine. *Aneurysm Clipping / Cincinnati, OH Mayfield Brain & Spine*. <https://mayfieldclinic.com/pe-clipping.htm>. 1.202.
- [7] Brain Aneurysm Foundation. *Surgical Treatment: Clipping - Brain Aneurysm Foundation*. <https://bafound.org/treatment/surgical-treatment-clipping/>. Apr. 2019.
- [8] M.D. The Neurosurgical Atlas by Aaron Cohen-Gadol. *Sylvian Fissure Split: Small MCA Aneurysm*. <https://www.neurosurgicalatlas.com/cases/sylvian-fissure-split-small-mca-aneurysm>. 1.2015.
- [9] Babu G. Welch, Rafael de Oliveira Sillero, Jonathan A. White, and H. Hunt Batjer. “Chapter 14 - Technical Principles of Aneurysm Clipping”. In: *Intracranial Aneurysms*. Ed. by Andrew J. Ringer. Academic Press, 2018, pp. 207–232. ISBN: 978-0-12-811740-8. DOI: <https://doi.org/10.1016/B978-0-12-811740-8.00014-9>. URL: <http://www.sciencedirect.com/science/article/pii/B9780128117408000149>.

-
- [10] Brian M. Howard and Daniel L. Barrow. “9 - Intraoperative Rupture and Parent Artery Injury During Aneurysm Surgery”. In: *Complications in Neurosurgery*. Ed. by Anil Nanda. London: Content Repository Only!, 2019, pp. 37–42. ISBN: 978-0-323-50961-9. DOI: <https://doi.org/10.1016/B978-0-323-50961-9.00009-8>. URL: <http://www.sciencedirect.com/science/article/pii/B9780323509619000098>.
 - [11] Chad W. Washington, Tao Ju, Gregory J. Zipfel, and Ralph G. Dacey. “Middle Cerebral Artery Bifurcation Aneurysms: An Anatomic Classification Scheme for Planning Optimal Surgical Strategies”. In: *Neurosurgery* 10 Issue 1.1 (2014), pp. 145–155. DOI: 10.1227/NEU.00000000000000250.
 - [12] Hong J. Jeon, So Y. Kim, Keun Y. Park, Jae W. Lee, and Seung K. Huh. “Ideal clipping methods for unruptured middle cerebral artery bifurcation aneurysms based on aneurysmal neck classification”. In: *Neurosurgical Review* 39.2 (2016), pp. 215–224. DOI: 10.1007/s10143-015-0671-x.
 - [13] Yoko Kato. “A New Classification Of Unruptured Middle Cerebral Artery Bifurcation Aneurysms”. In: 2014.
 - [14] Georgios A. Maragkos, Adam A. Dmytriw, Mohamed M. Salem, Vincent M. Tutino, Hui Meng, Christophe Cognard, Paolo Machi, Timo Krings, and Vitor Mendes Pereira. “Overview of Different Flow Diverters and Flow Dynamics”. In: *Neurosurgery* 86 (2020), S21–S34. DOI: 10.1093/neuros/nyz323.
 - [15] Laurent Pierot, Joachim Klisch, Christophe Cognard, Istvan Szikora, Benjamin Mine, Krzysztof Kadziolka, Wojtech Sychra, Istvan Gubucz, Anne-Christine Januel, and Boris Lubicz. “Endovascular WEB Flow Disruption in Middle Cerebral Artery Aneurysms: Preliminary Feasibility, Clinical, and Anatomical Results in a Multi-center Study”. In: *Neurosurgery* 73.1 (2013), pp. 27–35. DOI: 10.1227/01.neu.0000429860.04276.c1.
 - [16] Ning Lin, Kevin Cahill, Kai Frerichs, Robert Friedlander, and Elizabeth Claus. “Treatment of ruptured and unruptured cerebral aneurysms in the USA: A paradigm shift”. In: *Journal of neurointerventional surgery* 4 (June 2011), pp. 182–9. DOI: 10.1136/jnis.2011.004978.
 - [17] Jennifer McDonald, Robert McDonald, Jiaquan Fan, David Kallmes, Giuseppe Lanzino, and Harry Cloft. “Comparative Effectiveness of Unruptured Cerebral Aneurysm Therapies Propensity Score Analysis of Clipping Versus Coiling”. In: *Stroke; a journal of cerebral circulation* 44 (Feb. 2013). DOI: 10.1161/STROKEAHA.111.000196.
 - [18] Kishor Choudhari, Moncompu Ramachandran, Mark McCarron, and Chandrasekaran Kaliaperumal. “Aneurysms unsuitable for endovascular intervention: Surgical outcome and management challenges over a 5-year period following International Subarachnoid Haemorrhage Trial (ISAT)”. In: *Clinical neurology and neurosurgery* 109 (Jan. 2008), pp. 868–75. DOI: 10.1016/j.clineuro.2007.09.022.
 - [19] Toshikazu Kimura, Akio Morita, Kengo Nishimura, Hitoshi Aiyama, Hirotaka Ito, Syunsuke Fukaya, Shigeo Sora, and Chikayuki Ochiai. “Simulation of and training for cerebral aneurysm clipping with 3-dimensional models”. In: *Neurosurgery* 65 (Oct. 2009), 719–25, discussion 725. DOI: 10.1227/01.NEU.0000354350.88899.07.
-

-
- [20] Stephan Reichelt, Ralf Haeussler, Gerald Fütterer, and Norbert Leister. “Depth cues in human visual perception and their realization in 3D displays”. In: *Proceedings of SPIE 7690, Three-Dimensional Imaging, Visualization, and Display 2010 and Display Technologies and Applications for Defense, Security, and Avionics IV*. International Society for Optics and Photonics. 2010, pp. 92–103. DOI: 10.1117/12.850094. URL: <https://doi.org/10.1117/12.850094>.
 - [21] Rick Van Krevelen and Ronald Poelman. “A Survey of Augmented Reality Technologies, Applications and Limitations”. In: *International Journal of Virtual Reality (ISSN 1081-1451)* 9 (June 2010), p. 1. DOI: 10.20870/IJVR.2010.9.2.2767.
 - [22] Rositsa Bogdanova, Pierre Boulanger, and Bin Zheng. “Depth Perception of Surgeons in Minimally Invasive Surgery”. In: *Surgical Innovation* 23 (Mar. 2016). DOI: 10.1177/1553350616639141.
 - [23] D. J. Aks and J. T. Enns. “Visual search for size is influenced by a background texture gradient”. In: *Journal of Experimental Psychology: Human Perception and Performance* 22 (1996), pp. 1467–1481. DOI: <https://doi.org/10.1037/0096-1523.22.6.1467>.
 - [24] Ali Alaraj, Cristian Luciano, Daniel Bailey, Abdussalam Elsenousi, Ben Roitberg, Antonio Bernardo, P Banerjee, and Fady Charbel. “Virtual Reality Cerebral Aneurysm Clipping Simulation With Real-Time Haptic Feedback”. In: *Neurosurgery* 11 Suppl 2 (Jan. 2015). DOI: 10.1227/NEU.0000000000000583.
 - [25] Matthias Gmeiner, Johannes Dirnberger, Wolfgang Fenz, Maria Gollwitzer, Gabriele Wurm, Johannes Trenkler, and Andreas Gruber. “Virtual Cerebral Aneurysm Clipping with Real-Time Haptic Force Feedback in Neurosurgical Education”. In: *World Neurosurgery* 112 (Jan. 2018). DOI: 10.1016/j.wneu.2018.01.042.
 - [26] Toshihiro Mashiko, Keisuke Otani, Ryutaro Kawano, Takehiko Konno, Naoki Kaneko, Yumiko Ito, and Eiju Watanabe. “Development of Three-Dimensional Hollow Elastic Model for Cerebral Aneurysm Clipping Simulation Enabling Rapid and Low Cost Prototyping”. In: *World neurosurgery* 83 (Oct. 2013). DOI: 10.1016/j.wneu.2013.10.032.
 - [27] Naoyuki Shono, Taichi Kin, Seiji Nomura, Satoru Miyawaki, Toki Saito, Hideaki Imai, Hirofumi Nakatomi, Hiroshi Oyama, and Nobuhito Saito. “Microsurgery Simulator of Cerebral Aneurysm Clipping with Interactive Cerebral Deformation Featuring a Virtual Arachnoid”. In: *Operative Neurosurgery* 14 (Aug. 2017). DOI: 10.1093/ons/opx155.
 - [28] Sergio Teodoro Vite, César Domínguez Velasco, Aldo Francisco Hernández Valencia, Juan Salvador Pérez Lomelí, and Miguel Ángel Padilla Castañeda. “Virtual Simulation of Brain Sylvian Fissure Exploration and Aneurysm Clipping with Haptic Feedback for Neurosurgical Training”. In: *Augmented Reality, Virtual Reality, and Computer Graphics*. Ed. by Lucio Tommaso De Paolis and Patrick Bourdot. Cham: Springer International Publishing, 2018, pp. 230–238. ISBN: 978-3-319-95281-9.
 - [29] R. Gasteiger, M. Neugebauer, O. Beuing, and B. Preim. “The FLOWLENS: A Focus-and-Context Visualization Approach for Exploration of Blood Flow in Cerebral Aneurysms”. In: *IEEE Transactions on Visualization and Computer Graphics* 17.12 (2011), pp. 2183–2192.
-

-
- [30] Sylvia Saalfeld, Kai Lawonn, Thomas Hoffmann, Martin Skalej, and Bernhard Preim. “Combined Visualization of Wall Thickness and Wall Shear Stress for the Evaluation of Aneurysms”. In: *IEEE Transactions on Visualization and Computer Graphics* 20 (Nov. 2014). DOI: 10.1109/TVCG.2014.2346406.
 - [31] Marta Kersten-Oertel, Pierre Jannin, and D. L. Collins. “The state of the art of visualization in mixed reality image guided surgery”. English. In: *Computerized Medical Imaging and Graphics* 37.2 (2013), pp. 98–112. DOI: 10.1016/j.compmedimag.2013.01.009.
 - [32] Luc Soler, Nicholas Ayache, Stéphane Nicolau, Xavier Pennec, Clément Forest, Hervé Delingette, Didier Mutter, and Jacques Marescaux. “Virtual Reality, Augmented Reality and Robotics in surgical procedures of the liver”. In: *Perspectives in Image-guided Surgery. Proceedings of the Scientific Workshop on Medical Robotics, Navigation and Visualization (MRNV) 2004*. RheinAhrCampus Remagen, Germany, Germany: World Scientific, 2004, pp. 476–484. URL: <https://hal.inria.fr/inria-00615975>.
 - [33] Jaime Giraldez, Haydar Talib, Marco Caversaccio, and Miguel Ángel González Ballester. “Multimodal augmented reality system for surgical microscopy - art. no. 61411S”. In: *Proceedings of SPIE - The International Society for Optical Engineering*. Vol. 6141. Mar. 2006. DOI: 10.1117/12.651267.
 - [34] Takakazu Kawamata, Hiroshi Iseki, Takao Shibasaki, and Tomokatsu Hori. “Endoscopic Augmented Reality Navigation System for Endonasal Transsphenoidal Surgery to Treat Pituitary Tumors: Technical Note”. In: *Neurosurgery* 50 (June 2002), pp. 1393–1397. DOI: 10.1227/00006123-200206000-00038.
 - [35] Darko Katić, Gunther Sudra, Stefanie Speidel, Gregor Castrillón Oberndorfer, Georg Eggers, and Rüdiger Dillmann. “Knowledge-based Situation Interpretation for Context-aware Augmented Reality in Dental Implant Surgery”. In: *Medical imaging and augmented reality: Proceedings of the 5th international workshop (MIAR 2010), Beijing, China, September 19 - 20, 2010. Ed.: H. Liao*. Vol. 6326. Lecture notes in computer science. Springer, Heidelberg, 2010, pp. 531–540. ISBN: 978-3-642-15699-1.
 - [36] Jochen Suessmuth, Wassilios-Daniele Protogerakis, Alexander Piazza, Frank Enders, Ramin Naraghi, Günther Greiner, and Peter Hastreiter. “Color-encoded distance visualization of cranial nerve-vessel contacts”. In: *International journal of computer assisted radiology and surgery* 5 (Apr. 2010), pp. 647–54. DOI: 10.1007/s11548-010-0410-2.
 - [37] Christian Dick, Rainer Burgkart, and Rüdiger Westermann. “Distance Visualization for Interactive 3D Implant Planning”. In: *IEEE transactions on visualization and computer graphics* 17 (Dec. 2011), pp. 2173–82. DOI: 10.1109/TVCG.2011.189.
 - [38] Christian Hansen, Jan Wieferich, Felix Ritter, Christian Rieder, and Heinz-Otto Peitgen. “Illustrative visualization of 3D planning models for augmented reality in liver surgery”. In: *International journal of computer assisted radiology and surgery* 5 (Mar. 2010), pp. 133–41. DOI: 10.1007/s11548-009-0365-3.
 - [39] Daniela Trevisan, Luciana Nedel, Benoit Macq, and Jean Vanderdonckt. “Detecting interaction variables in a mixed reality system for maxillofacial-guided surgery”. In: *Proceedings of International Conference on Medical Imaging SPIE2003*. Vol. 5029. 15-20. International Societyfor Optical Engineering, Jan. 2006, pp. 108–118.
-

-
- [40] Noeska Smit, Kai Lawonn, Anne Kraima, Marco Deruiter, Hessam Sokooti, Stefan Bruckner, Elmar Eisemann, and Anna Vilanova. “PelVis: Atlas-based Surgical Planning for Oncological Pelvic Surgery”. In: *IEEE Transactions on Visualization and Computer Graphics (Proceedings of Scientific Visualization 2016)* 23 (Jan. 2017). DOI: 10.1109/TVCG.2016.2598826.
 - [41] Christian Winne, Martin Khan, Fabian Stopp, Emanuel Jank, and Erwin Keeve. “Overlay visualization in endoscopic ENT surgery”. In: *International journal of computer assisted radiology and surgery* 6 (May 2011), pp. 401–6. DOI: 10.1007/s11548-010-0507-7.
 - [42] Florian Heinrich, Gerd Schmidt, Kai Bornemann, Anna L. Roethe, Walid I. Essayed, and Christian Hansen. “Visualization Concepts to Improve Spatial Perception for Instrument Navigation in Image-Guided Surgery”. In: *Proceedings of SPIE 10951, Proceedings Volume 10951, Medical Imaging 2019: Image-Guided Procedures, Robotic Interventions, and Modeling*. Mar. 2019. URL: <https://doi.org/10.1117/12.2512761>.
 - [43] M. Meuschke, S. Voss, O. Beuing, B. Preim, and K. Lawonn. “Combined Visualization of Vessel Deformation and Hemodynamics in Cerebral Aneurysms”. In: *IEEE Transactions on Visualization and Computer Graphics* 23.1 (2017), pp. 761–770.
 - [44] M. Meuschke, S. Voss, O. Beuing, B. Preim, and K. Lawonn. “Glyph-Based Comparative Stress Tensor Visualization in Cerebral Aneurysms”. In: *Comput. Graph. Forum* 36.3 (June 2017), pp. 99–108. ISSN: 0167-7055. DOI: 10.1111/cgf.13171. URL: <https://doi.org/10.1111/cgf.13171>.
 - [45] Christian Dick, Joachim Georgii, Rainer Burgkart, and Rüdiger Westermann. “Stress Tensor Field Visualization for Implant Planning in Orthopedics”. In: *IEEE Transactions on Visualization and Computer Graphics (Proceedings of IEEE Visualization 2009)* 15.6 (2009), pp. 1399–1406.
 - [46] Rita Borgo, Johannes Kehler, David Chung, Eamonn Maguire, Robert Laramee, Helwig Hauser, Matthew Ward, and Min Chen. “Glyph-based Visualization: Foundations, Design Guidelines, Techniques and Applications”. In: *Eurographics*. May 2013. DOI: 10.2312/conf/EG2013/stars/039-063.
 - [47] Philip Quinlan and Glyn Humphreys. “Visual search for targets defined by combinations of color, shape, and size: An examination of the task constraints on feature and conjunction searches”. In: *Perception & psychophysics* 41 (June 1987), pp. 455–72. DOI: 10.3758/BF03203039.
 - [48] L. Williams. “The effect of target specification on objects fixated during visual search”. In: *Perception & Psychophysics* 1 (1966), pp. 315–318.
 - [49] Timo Ropinski, Steffen Oeltze, and Bernhard Preim. “Survey of glyph-based visualization techniques for spatial multivariate medical data”. English. In: *Computers & Graphics* 35.2 (2011), pp. 392–401. DOI: 10.1016/j.cag.2011.01.011.
 - [50] Rainer Wegenkittl, Eduard Gröller, and Werner Purgathofer. “Animating flow fields: rendering of oriented line integral convolution”. In: 1997, pp. 15–21.
 - [51] Samuel Silva, Beatriz Santos, and Joaquim Madeira. “Using color in visualization: A survey”. In: *Computers & Graphics* 35 (Apr. 2011), pp. 320–333. DOI: 10.1016/j.cag.2010.11.015.
-

-
- [52] Cynthia A. Brewer. *Designing better maps: a guide for GIS users*. English. 1. Redlands, Calif: ESRI Press, 2005. ISBN: 9781589484405.
 - [53] Kenneth Moreland. “Diverging Color Maps for Scientific Visualization”. In: *Proceedings of the 5th International Symposium on Advances in Visual Computing: Part II*. ISVC '09. Las Vegas, Nevada: Springer-Verlag, 2009, pp. 92–103. ISBN: 9783642105197. DOI: 10.1007/978-3-642-10520-3_9. URL: https://doi.org/10.1007/978-3-642-10520-3_9.
 - [54] David Borland and M Taylor. “Rainbow Color Map (Still) Considered Harmful”. In: *IEEE computer graphics and applications* 27 (Mar. 2007), pp. 14–7. DOI: 10.1109/MCG.2007.323435.
 - [55] C. Li, J. Ding, Z. Hong, Y. Pan, and P. X. Liu. “A Surface Mass-Spring Model With New Flexion Springs and Collision Detection Algorithms Based on Volume Structure for Real-Time Soft-Tissue Deformation Interaction”. In: *IEEE Access* 6 (2018), pp. 75572–75597.
 - [56] Yuping Duan, Weimin Huang, Huibin Chang, Wenyu Chen, Kyaw Kyar Toe, Jiayin Zhou, Tao Yang, Jiang Liu, Soo Kng Teo, Chi Wan Lim, Yi Su, Chee Kong Chui, and Stephen Chang. “Modeling and Simulation of Soft Tissue Deformation”. In: *Proceedings of Abdominal Imaging. Computation and Clinical Applications*. Ed. by Hiroyuki Yoshida, Simon Warfield, and Michael W. Vannier. Berlin, Heidelberg: Springer Berlin Heidelberg, 2013, pp. 221–230. ISBN: 978-3-642-41083-3.
 - [57] Kathrin Weber. “Interaktive Echtzeitsimulation deformierbarer Oberflächen für Trainingssysteme in der Augenchirurgie”. PhD thesis. Universität Mannheim, 2009.
 - [58] Wouter Mollemans, Filip Schutyser, Johan Van Cleynenbreugel, and Paul Suetens. “Fast Soft Tissue Deformation with Tetrahedral Mass Spring Model for Maxillofacial Surgery Planning Systems”. In: *Proceedings of Medical Image Computing and Computer-Assisted Intervention – MICCAI 2004*. Ed. by Christian Barillot, David R. Haynor, and Pierre Hellier. Berlin, Heidelberg: Springer Berlin Heidelberg, 2004, pp. 371–379. ISBN: 978-3-540-30136-3.
 - [59] Sylvester Arnab and Vinesh Raja. “A Deformable Surface Model with Volume Preserving Springs”. In: *Proceedings of Articulated Motion and Deformable Objects: 5th International Conference, AMDO 2008*. Vol. 5098. July 2008, pp. 259–268. DOI: 10.1007/978-3-540-70517-8_25.
 - [60] Mesit Jaruwan and Chaudhry Shafaq. “3D Soft Body Simulation Using Mass-spring System with Internal Pressure Force and Simplified Implicit Integration”. In: *Journal of Computers* 2 (Oct. 2007). DOI: 10.4304/jcp.2.8.34–43.
 - [61] Tiantian Liu, Adam W. Bargteil, James F. O’Brien, and Ladislav Kavan. “Fast Simulation of Mass-Spring Systems”. In: *ACM Trans. Graph.* 32.6 (Nov. 2013). ISSN: 0730-0301. DOI: 10.1145/2508363.2508406. URL: <https://doi.org/10.1145/2508363.2508406>.
 - [62] Yuping Duan, Weimin Huang, Huibin Chang, Wenyu Chen, Jiayin Zhou, Soo-Kng Teo, Yi Su, Chee-Kong Chui, and Stephen Chang. “Volume Preserved Mass-Spring Model with Novel Constraints for Soft Tissue Deformation”. In: *IEEE journal of biomedical and health informatics* 20 (Nov. 2014). DOI: 10.1109/JBHI.2014.2370059.
-

-
- [63] Andrew B. Mor, Omar Ghattas, Branislav Jaramaz, and Sarah F. Frisken. “Progressive Cutting with Minimal New Element Creation of Soft Tissue Models for Interactive Surgical Simulation”. PhD thesis. Carnegie Mellon University, 2001.
 - [64] T. Halic, S. Kockara, C. Bayrak, R. Rowe, and B. Chen. “Soft Tissue Deformation and Optimized Data Structures for Mass Spring Methods”. In: *Proceedings of 2009 Ninth IEEE International Conference on Bioinformatics and BioEngineering*. 2009, pp. 45–52.
 - [65] M. Levoy. “Display of surfaces from volume data”. In: *IEEE Computer Graphics and Applications* 8.3 (1988), pp. 29–37.
 - [66] Byeong-Seok Shin and Suk Hyun Lim. “An Efficient Navigation Method for Virtual Endoscopy Using Volume Ray Casting”. In: *Proceedings of Computational Science — ICCS 2003*. Ed. by Peter M. A. Sloot, David Abramson, Alexander V. Bogdanov, Yuriy E. Gorbachev, Jack J. Dongarra, and Albert Y. Zomaya. Berlin, Heidelberg: Springer Berlin Heidelberg, 2003, pp. 60–69. ISBN: 978-3-540-44863-1.
 - [67] Roman Vlasov, Karl Friese, and Franz-Erich Wolter. “Haptic Rendering of Volume Data with Collision Determination Guarantee Using Ray Casting and Implicit Surface Representation”. In: *Proceedings of the 2012 International Conference on Cyberworlds, Cyberworlds 2012*. Sept. 2012. DOI: 10.1109/CW.2012.20.
 - [68] Ahmed Elsharkawy, Martin Lehečka, Mika Niemelä, Romain Billon-Grand, Hanna Lehto, Riku Kivisaari, and Juha Hernesniemi. “A New, More Accurate Classification of Middle Cerebral Artery Aneurysms: Computed Tomography Angiographic Study of 1009 Consecutive Cases With 1309 Middle Cerebral Artery Aneurysms”. In: *Neurosurgery* 73.1 (Apr. 2013), pp. 94–102. ISSN: 0148-396X. DOI: 10.1227/01.neu.0000429842.61213.d5. eprint: <https://academic.oup.com/neurosurgery/article-pdf/73/1/94/32595476/neurosurgery-73-1-94.pdf>. URL: <https://doi.org/10.1227/01.neu.0000429842.61213.d5>.
 - [69] Jang W. Yoon, Adnan H. Siddiqui, Travis M. Dumont, Elad I. Levy, L. N. Hopkins, Giuseppe Lanzino, Demetrius K. Lopes, Roham Moftakhar, Joshua T. Billingsley, Babu G. Welch, Alan S. Boulos, Junichi Yamamoto, Rabih G. Tawk, Andrew J. Ringer, Ricardo A. Hanel, and Endovascular Neurosurgery Research Group. “Feasibility and Safety of Pipeline Embolization Device in Patients With Ruptured Carotid Blister Aneurysms”. In: *Neurosurgery* 75.4 (2014), pp. 419–429. DOI: 10.1227/NEU.0000000000000487.
 - [70] ISO - International Organization of Standards. *ISO 9241-11:2018 Ergonomics of human-system interaction — Part 11: Usability: Definitions and concepts*. 2018.
 - [71] Max Wertheimer. “Laws of organization in perceptual forms”. In: *W. D. Ellis (Ed.), A source book of Gestalt psychology*. London: Routledge & Kegan Paul, 1938, pp. 71–88.
 - [72] Stephen E. Palmer. “Common region: a new principle of perceptual grouping”. In: *Cognitive psychology* 24.3 (1992), pp. 436–447. ISSN: 0010-0285. DOI: 10.1016/0010-0285(92)90014-s. URL: [https://doi.org/10.1016/0010-0285\(92\)90014-s](https://doi.org/10.1016/0010-0285(92)90014-s).
 - [73] R. Likert. “A Technique for the Measurement of Attitude Scales”. In: *Archives of Psychology* 22.140 (1932).
-

- [74] Maarten Someren, Yvonne Barnard, and Jacobijn Sandberg. *The Think Aloud Method - A Practical Guide to Modelling Cognitive Processes*. Jan. 1994.
 - [75] Jeff Rubin and Dana Chisnell. *Handbook of Usability Testing, Second Edition: How to Plan, Design, and Conduct Effective Tests*. Wiley Publishing, Inc., 2008. ISBN: 978-0-470-18548-3.
-

Appendix

Aneurysm Clipping Tool

Einleitung und Datenschutzhinweise

Hallo und herzlich willkommen zu meiner Umfrage!

Diese Umfrage dient der Evaluierung meiner Masterarbeit, um herauszufinden, wie nützlich verschiedene Visualisierungskonzepte im Kontext einer Aneurysmen Clipping Simulation sind. Solch eine Simulation soll Chirurgen und Medizinstudenten zu Übungszwecken dienen.

Vielen Dank für Ihre Unterstützung!

★ Datenschutzhinweise

☐ Ich habe die in der Fußnote hinterlegten Datenschutzhinweise gelesen und akzeptiert

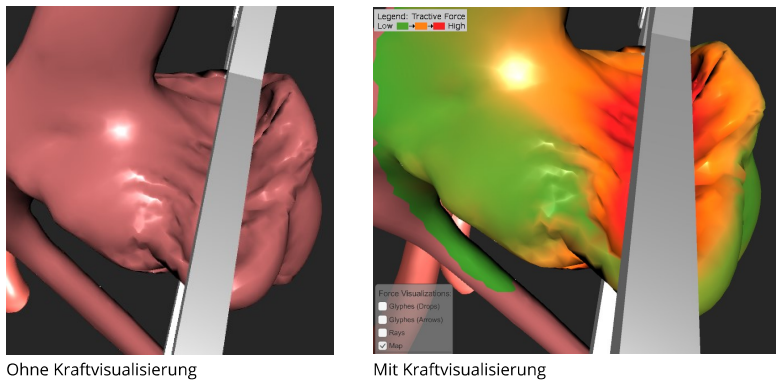
Impressum: Mareen Allgaier, Otto-von-Guericke Universität Magdeburg | [Datenschutzerklärung](#)

Aneurysm Clipping Tool

Visualisierungskonzepte: Zugkraft - Map

Im folgenden Abschnitt werden verschiedene Visualisierungen vorgestellt. Diese zeigen die Verschiebung der Gefäßwand, die beim Clipping durch den auftretenden Zug verursacht wird. Es folgt eine einzelne Auswertung der Visualisierungskonzepte und ein anschließender Vergleich. Bitte bewerten Sie dabei nicht die Platzierung des Clips.

Das erste Visualisierungskonzept ist eine Karte auf der Gefäßoberfläche, die die Stärke der Verschiebung farblich darstellt. Rot sind dabei hohe Werte, grün kleine.



Ohne Kraftvisualisierung

Mit Kraftvisualisierung

★ Bitte bewerten Sie die folgenden Punkte bezüglich der Kraftvisualisierung.

Bewerten Sie von **1 = trifft nicht zu** bis **5 = trifft zu**

	1	2	3	4	5
Die Visualisierung ist intuitiv	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Sie bietet zusätzliche Informationen	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Sie bringt einen Mehrwert	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Das Gefäß und relevante Informationen werden nicht verdeckt	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Sie können Bereiche mit starkem Zug gut lokalisieren	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Sie können erkennen in welche Richtung die Oberfläche gezogen wird	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Sie können sich vorstellen, diese Visualisierung in einem entsprechenden Tool zu verwenden	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

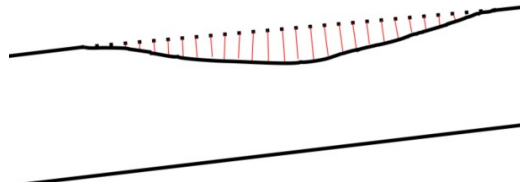
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 LamaPoll

Aneurysm Clipping Tool

Visualisierungskonzepte: Zugkraft - Rays

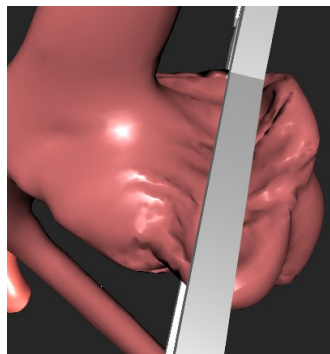
Das zweite Visualisierungskonzept sind Strahlen. Ein Strahl zeigt für einen Oberflächenpunkt die Verbindung zwischen Ausgangsposition und verschobener Position an (siehe 2D-Skizze). Farblich wird auch hier die Stärke der Verschiebung angezeigt.



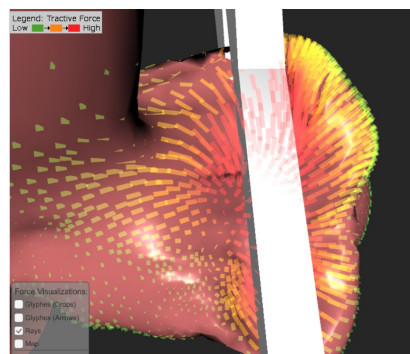
2D-Skizze der Rays

Punkte: ursprungspositionen

Rote Linien: Strahlen von der ursprungsposition zu der neue Position



Ohne Kraftvisualisierung



Mit Kraftvisualisierung

★ Bitte bewerten Sie die folgenden Punkte bezüglich der Kraftvisualisierung.

Bewerten Sie von **1 = trifft nicht zu** bis **5 = trifft zu**

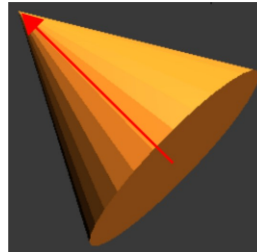
	1	2	3	4	5
Die Visualisierung ist intuitiv	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Sie bietet zusätzliche Informationen	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Sie bringt einen Mehrwert	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Das Gefäß und relevante Informationen werden nicht verdeckt	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Sie können Bereiche mit starkem Zug gut lokalisieren	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Sie können erkennen in welche Richtung die Oberfläche gezogen wird	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Sie können sich vorstellen, diese Visualisierung in einem entsprechenden Tool zu verwenden	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

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Aneurysm Clipping Tool

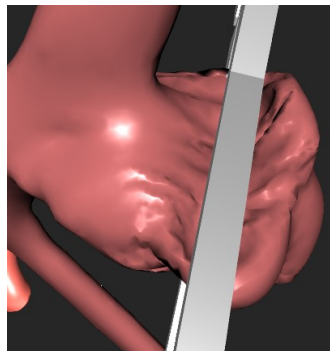
Visualisierungskonzepte: Zugkraft - Arrows

Das dritte Visualisierungskonzept sind Pfeilglyphen. Diese zeigen die Richtung der Verschiebung durch ihre Ausrichtung und die Stärke über die Farbe an (siehe Skizze der Glyphe).

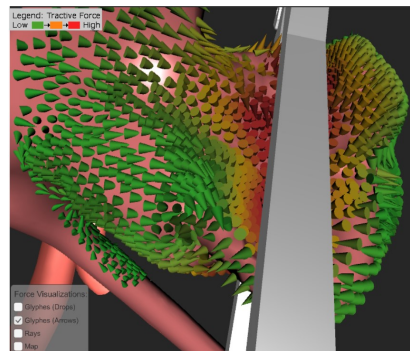


Skizze der Glyphen

(Roter Pfeil: Hauptausrichtung ▲ Verschiebungsrichtung,
Farbe ▲ Stärke der Verschiebung)



Ohne Kraftvisualisierung



Mit Kraftvisualisierung

★ Bitte bewerten Sie die folgenden Punkte bezüglich der Kraftvisualisierung.

Bewerten Sie von **1 = sehr schlecht** bis **5 = sehr gut**

	1	2	3	4	5
Die Visualisierung ist intuitiv	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Sie bietet zusätzliche Informationen	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Sie bringt einen Mehrwert	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Das Gefäß und relevante Informationen werden nicht verdeckt	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Sie können Bereiche mit starkem Zug gut lokalisieren	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Sie können erkennen in welche Richtung die Oberfläche gezogen wird	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Sie können sich vorstellen, diese Visualisierung in einem entsprechenden Tool zu verwenden	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

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Aneurysm Clipping Tool

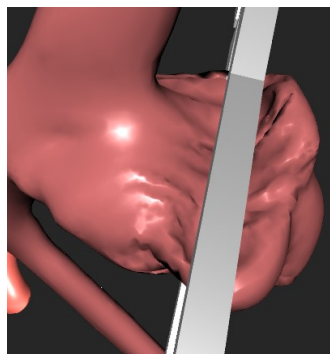
Visualisierungskonzepte: Zugkraft - Drops

Das vierte Visualisierungskonzept sind Glyphen in Tropfenform. Diese zeigen die Richtung der Verschiebung durch ihre Ausrichtung. Wie bei einem Tropfen ist Vorne durch die Rundung charakterisiert. Die Stärke wird zusätzlich zur Farbe noch über die Transparenz und Länge der Glyphen angegeben. (siehe Skizze der Glyphe)

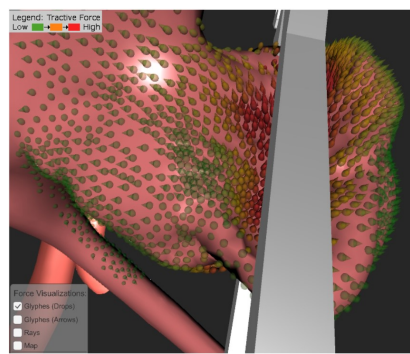


Skizze der Glyphe

(Roter Pfeil: Hauptausrichtung Δ Verschiebungsrichtung,
Blau: Länge der Glyphe Δ Stärke der Verschiebung,
Farbe und Transparenz Δ Stärke der Verschiebung)



Ohne Kraftvisualisierung



Mit Kraftvisualisierung

★ Bitte bewerten Sie die folgenden Punkte bezüglich der Kraftvisualisierung.

Bewerten Sie von **1 = trifft nicht zu** bis **5 = trifft zu**

	1	2	3	4	5
Die Visualisierung ist intuitiv	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Sie bietet zusätzliche Informationen	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Sie bringt einen Mehrwert	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Das Gefäß und relevante Informationen werden nicht verdeckt	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Sie können Bereiche mit starkem Zug gut lokalisieren	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Sie können erkennen in welche Richtung die Oberfläche gezogen wird	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Sie können sich vorstellen, diese Visualisierung in einem entsprechenden Tool zu verwenden	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

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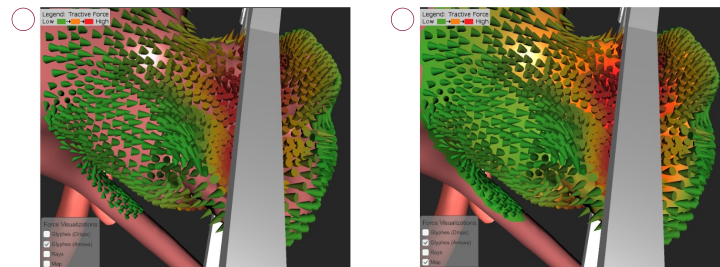
Aneurysm Clipping Tool

Visualisierungskonzepte: Zugkraft - Kombination

Weiterhin werden die zwei Glyphenkonzepte mit der Farbkarte kombiniert. Geben Sie an, ob Sie die Glyphen ohne zusätzliche farbige Unterlegung oder mit bevorzugen.

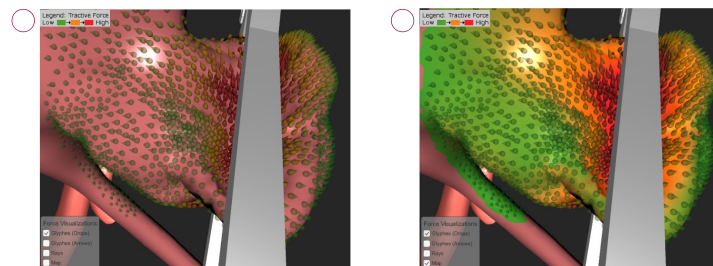
★ Auswahl der Pfeilglyphe

Wählen Sie Ihre bevorzugte Variante



★ Auswahl der Pfeilglyphe

Wählen Sie Ihre bevorzugte Variante



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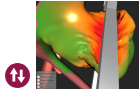
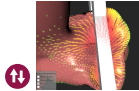
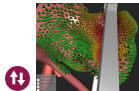
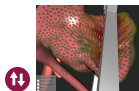
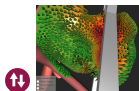
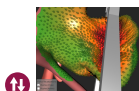
Umfrage erstellt mit
 LamaPoll

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Visualisierungskonzepte: Zugkraft - Vergleich

- ★ Erstellen Sie ein Ranking der vorgestellten Konzepte.
Welches Konzept spricht Sie am meisten an?
Welches Konzept würden Sie am ehesten verwenden?

Ziehen Sie die wichtigen Elemente nach oben und ordnen Sie die unwichtigen Elemente nach unten.

	Farbkarte	<input type="text"/>
	Strahlen	<input type="text"/>
	Pfeilglyphen	<input type="text"/>
	Tropfenglyphen	<input type="text"/>
	Pfeilglyphen mit Farbkarte	<input type="text"/>
	Tropfenglyphen mit Farbkarte	<input type="text"/>

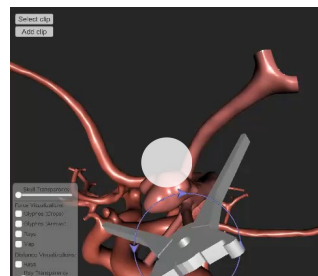
Haben Sie weitere Fragen, Wünsche, Kritik oder Anregungen bezüglich der Visualisierungen der Zugkraft?

Aneurysm Clipping Tool

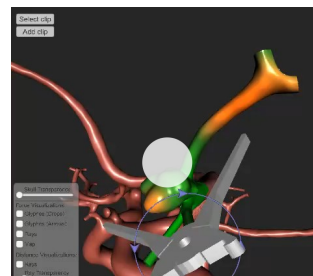
Visualisierungskonzepte: Distanz - Map

Im folgenden Abschnitt werden weitere Visualisierungen vorgestellt. Diese zeigen die Distanz zwischen dem Clip und der Gefäßwand an. Sie sollen helfen, den Clip besser navigieren zu können, da in einer 3D-Anwendung auf einem 2D-Bildschirm die Tiefenabschätzung sehr eingeschränkt ist.

Im erste Visualisierungskonzept wird eine Karte auf der Gefäßoberfläche abgebildet, die die Distanz zum Clip verdeutlicht. Hierfür dient eine Regenbogenfarbskala, das bedeutet, die Distanz ist von rot, gelb, grün, blau zu violett aufsteigend.



Ohne Distanzvisualisierung



Legend: Distance
Low → High
Mit Distanzvisualisierung

★ Wählen Sie Ihre bevorzugte Variante der zwei Videos.

☐ Ohne Distanzvisualisierung ☐ Mit Distanzvisualisierung

★ Bitte bewerten Sie die vorgestellte Distanzvisualisierung.

Bewerten Sie von **1 = trifft nicht zu** bis **5 = trifft zu**

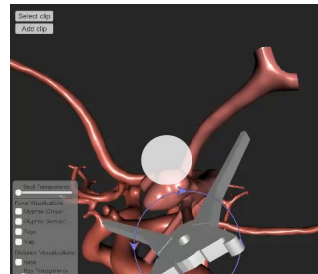
	1	2	3	4	5
Die Visualisierung ist intuitiv	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Sie bietet zusätzliche Informationen	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Ihrer Meinung nach unterstützt diese Visualisierung die Navigation	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Die Visualisierung gibt Ihnen ein besseres Verständnis der räumlichen Relationen und Distanzen	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Das Gefäß und relevante Informationen werden nicht verdeckt	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Sie können nahe Bereiche gut erkennen	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Sie können sich vorstellen, diese Visualisierung in einem entsprechenden Tool zu verwenden	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

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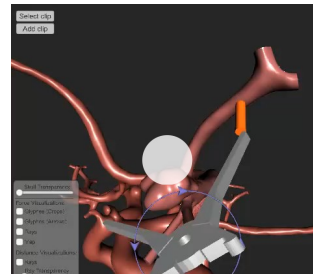
Aneurysm Clipping Tool

Visualisierungskonzepte: Distanz - Cylinder

Das zweite Visualisierungskonzept ist ein Zylinder, der die geringste Distanz zwischen Clip und Gefäß darstellt. Die Farbkodierung entspricht der vorherigen Farbkarte.



Ohne Distanzvisualisierung



Legend: Distance
Low → High
Mit Distanzvisualisierung

★ Wählen Sie Ihre bevorzugte Variante der zwei Videos.

☐ Ohne Distanzvisualisierung ☐ Mit Distanzvisualisierung

★ Bitte bewerten Sie die vorgestellte Distanzvisualisierung

Bewerten Sie von 1 = trifft nicht zu bis 5 = trifft zu

	1	2	3	4	5
Die Visualisierung ist intuitiv	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Sie bietet zusätzliche Informationen	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Ihrer Meinung nach unterstützt diese Visualisierung die Navigation	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Die Visualisierung gibt Ihnen ein besseres Verständnis der räumlichen Relationen und Distanzen	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Das Gefäß und relevante Informationen werden nicht verdeckt	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Sie können nahe Bereiche gut erkennen	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Sie können sich vorstellen, diese Visualisierung in einem entsprechenden Tool zu verwenden	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

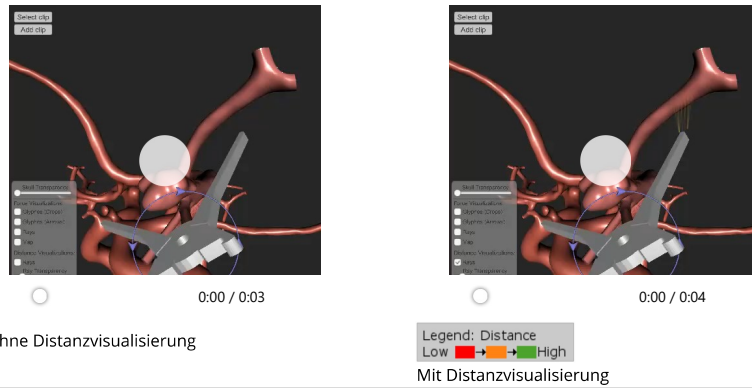
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Aneurysm Clipping Tool

Visualisierungskonzepte: Distanz - Rays

Das dritte Visualisierungskonzept sind Strahlen, die nicht nur die kürzeste Distanz anzeigen, sondern alle Distanzen kleiner als ein gewisser Schwellenwert. Die Farben entsprechen der farblichen Abstufung der Farbkarte.



★ Wählen Sie Ihre bevorzugte Variante der zwei Videos.

☐ Ohne Distanzvisualisierung ☐ Mit Distanzvisualisierung

★ Bitte bewerten Sie die vorgestellte Distanzvisualisierung

Bewerten Sie von **1 = trifft nicht zu** bis **5 = trifft zu**

	1	2	3	4	5
Die Visualisierung ist intuitiv	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Sie bietet zusätzliche Informationen	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Ihrer Meinung nach unterstützt diese Visualisierung die Navigation	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Die Visualisierung gibt Ihnen ein besseres Verständnis der räumlichen Relationen und Distanzen	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Das Gefäß und relevante Informationen werden nicht verdeckt	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Sie können nahe Bereiche gut erkennen	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Sie können sich vorstellen, diese Visualisierung in einem entsprechenden Tool zu verwenden	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

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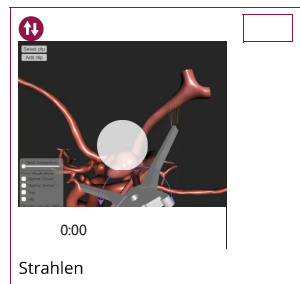
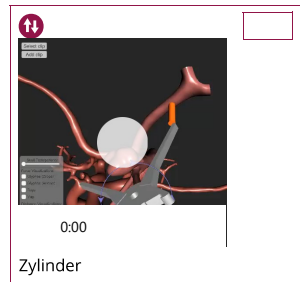
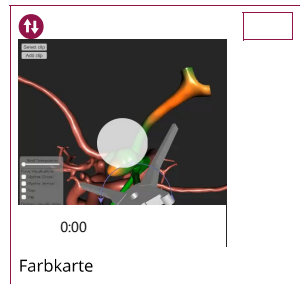
Umfrage erstellt mit
LamaPoll

Aneurysm Clipping Tool

Visualisierungskonzepte: Distanz- Vergleich

- ★ Erstellen Sie ein Ranking der vorgestellten Konzepte der Distanzvisualisierung.
Welches Konzept spricht Sie am meisten an?
Welches Konzept würden Sie am ehesten verwenden?

Ziehen Sie ansprechende Visualisierungen nach oben und ordnen Sie die weniger ansprechenden nach unten.



Umfrage erstellt mit
 LamaPoll