COMPUTER SUPPORTED PRE-OPERATIVE PLANNING OF CRANIOFACIAL SURGERY: FROM PATIENT TO TEMPLATE

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Abstract: Craniofacial malformations frequently implicate a high risk of medical complications and a negative psychological impact on the patient. In order to correct functional and aesthetic aspects of these malformations, skull reconstruction is required. Because of the complexity of the surgery, pre-operative planning is unavoidable. Current and previously developed planning environments often lack the opportunity to transfer the simulated surgery to the operation room on a cheap but accurate, and easy to handle basis [1]. This study applies an automated filter procedure, implemented in Matlab®, to generate a set of adapted contours from which a surface mesh can be directly deduced. Skull reconstruction planning is done on the generated outer bone surface model. For each resected/osteotomized bone part, the presented semi-automatic Matlab® procedure generates surface based bone cutting guides, also denoted bone segment templates. The clinical feasibility is validated by a succesful clinical case presenting a craniosynostosis patient showing severe anterior plagiocephaly combined with scaphocephaly.

Introduction

Craniofacial malformations frequently implicate a high risk of medical complications and a negative psychological impact on the patient. In order to correct functional and aesthetic aspects of these malformations, skull reconstruction - basically an iterative sequence of bone osteotomies and repositioning [2][3][4] - is required. Before virtual pre-operative planning and deduction of surface based bone cutting guides, an appropriate representation of the bone is required. Manually segmenting the bone from CT images is time consuming and highly user dependent. More advanced techniques are segmentation tools such as Boolean operations or region growing [Mimics®], or model based tools such as snakes or active shape models [5][6][7][8][9]. However, these techniques are sometimes unsuccessful in removing shape irregularities, processing bone defects or filtering redundant image information for the specified application.

The segmentation technique used for the surface based craniofacial applications presented in this paper consists of a straightforward grey level segmentation followed by a general filter, as developed by Gelaude *et al*. The extended filter procedure only retains contour information representing the outer bone surface as more specific internal contours, internal loops and shape irregularities are removed, tailoring the image for application. The developed medical image based design methodology can either convert a contour set of a specific bone type (e.g. neurocranium) to an outer surface triangulation mesh and vice versa. After surgery planning, the personalized outer surface mesh proves efficient to deduce bone cutting templates. A clinical craniosynostosis case illustrates this.

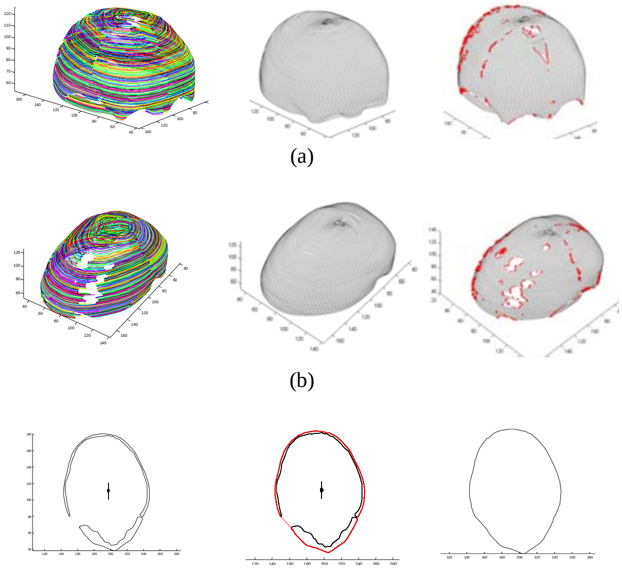
Craniosynostosis designates a skull malformation caused by premature fusion of one or more sutures in the cranial vault. Skull reconstruction planning is done on the generated outer bone surface model, after import in a commercially available planning environment. Current and previously developed environments often lack the opportunity to transfer the simulated surgery to the operation room on a cheap but accurate and easy to handle manner [1]. If transfer is incorporated either a simple screenshot or blue print with the obtained translation data is generated [10][11][12], or expensive and complex navigation and robot systems are required [3][13][14]. For each resected/osteotomized bone part, the presented semi-automatic procedure in this paper generates a three-dimensional triangulation mesh of a bone segment template, consisting of horizontal and vertical strips. Subsequently this three-dimensional template is unfolded to a two-dimensional and thus printable border diagram. Finally, a copy in sterile aluminium or plastic foil transfers the planning to the patient's cranium.

Materials and Methods

The general filter and mesh generating procedures for the outer bone surface will only be very concisely presented; full detail on this developed methodology is available elsewhere [15].

The bone contours are extracted from the patients CT data by quick grey value segmentation in Mimics®. Then, an extended filter procedure, developed in Matlab®, only retains contour information representing the outer surface of the bone as more specific internal contours, internal loops and shape irregularities are removed, tailoring the image for application. Finally, the developed medical image based design methodology can either convert a contour set of a specific bone type (e.g. neurocranium) to an outer surface triangulation mesh or convert a triangulation mesh to a basic contour set by means of a reslicing procedure.

A surface mesh is built from the spline set, created from the contours by the above-mentioned filter procedure. A grid of quadrilaterals is created after selecting a fixed number of points on each spline. If outer surface stitching was performed during filtering (Figure 1c) and extra hole information is available on the original contours, a procedure is now able to open the holes in the neurocranium mesh. In Figure 1a-b (right), these holes mainly represent the sutures in a neonatus skull. Quadrilaterals that completely reside in a hole are removed; the ones at the borders are adapted to the exact hole information in order to create a smooth transition between the slices. Finally, the surface mesh is closed at the top contour, with a Delaunay based triangulation.



(a)

(b)

(c)

Figure 1: Filtering outer bone surface from a neurocranium contour set of a neonatus with craniosynostosis (anterior plagiocephaly and scaphocephaly) in Matlab®

(a)-(b) Imported polyline set (left), resulting closed outer surface mesh (middle) and resulting outer surface mesh with opened sutures (right), seen from right frontal and occipital respectively.
(c) Outer surface stitching: Original slice (left), detected and stitched outer surface points on the contours (middle) and the final result for the slice (right).

Given an outer surface mesh of the neurocranium, one completely closed and one with opened sutures, surgery is simulated. Firstly, both meshes are exported in STL file format by triangulating each quadrilateral. Skull reconstruction planning is done on the exported closed outer bone surface model in a commercially available planning environment, e.g. Mimics® or Maxilim®. The closed mesh is preferred because this simplifies the deduction of the cutting guides out of the bone pieces afterwards. Due to software requirements – e.g. Mimics® is not capable of handling shells without thickness- the model could receive an internal offset of 1mm before import in the commercial planning environment. In order to provide the user with reference information, the viscerocranium is also visualised as an unfiltered volume STL, obtained by a swift region growing. Then the surgeon or technician reconstructs the skull with the available bone cutting, splitting and repositioning tools. The resected or osteotomized bone parts are finally reloaded in the developed Matlab® implementations for further processing.

For each resected/osteotomized bone part, a semi-automatic procedure generates a three-dimensional triangulation mesh of a bone segment template. As an entirely closed template is unpractical and prevents unfolding to a printable representation, a template consisting of horizontal and vertical strips is generated.

If the surface model was internally offset before, the outer surface shell of the 1mm thick part is detected and retained by means of a surface growing algorithm (Figure 2a). For a single triangle, neighbouring triangles are selected and processed recursively if the enclosed angle is smaller than a user defined threshold. Usually, a threshold value of 25 degrees provides the correct result. Then the user defines the position of the horizontal and vertical strips of the template in two distinct steps.

Firstly, the user indicates a cutting plane perpendicular to the bone surface by indicating a sequence of points. The resulting cutting line with the bone piece, also denoted as 'main intersection curve', is then retrieved (Figure 2b).

Secondly, the user indicates 'cross-planes' in every additionally indicated point on the main intersection curve (Figure 2c-d). Such cross-plane stands normal to the main horizontal plane and to the main intersection curve. On both sides of the indicated point, a parallel cross-plane is created at a user defined distance. The vertical intersection curves between bone piece and cross planes are calculated and once all vertical cross-sections are drawn, two additional horizontal cross-sections are performed above and below the main intersection curve. The obtained three-dimensional composition of cutting curves (Figure 2d) is then unfolded into a planar and thus printable representation, by drawing the lengths of all intersection curves in a plane, and connecting the ends of every threesome of related lines (Figure 2e).

Finally a triangulation mesh is calculated for the three-dimensional template strips by means of a convex Delaunay triangulation, adapted for concave contours (Figure 2f).

The STL representation of the template mesh is imported in the planning environment for a swift validation of the template position and outline, which is possible on the CT as well as on the three-dimensional visualisation of the neurocranium. For each resection/osteotomy, the position of the template is on the one hand defined by simulation screenshots and on the other hand by the distance from the template to reference points on the skull or on other templates. The available Mimics® or Maxilim® measurement and cephalometric tools facilitate the latter.

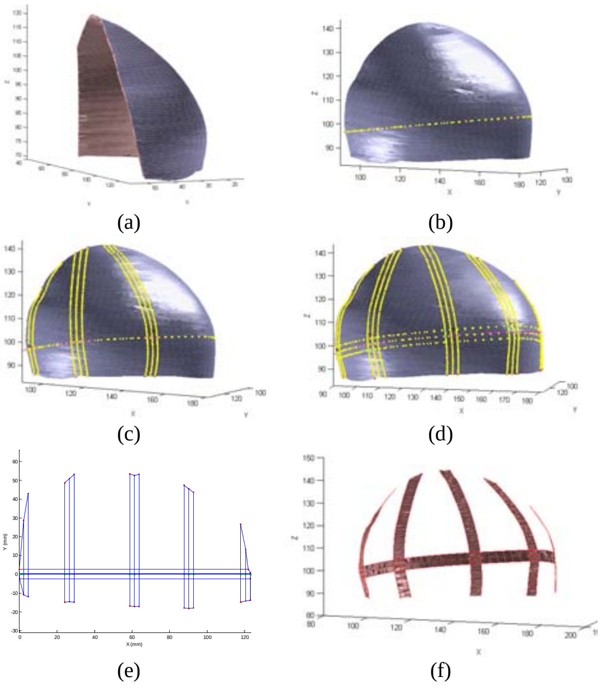

(a) (b) (c) (d) (e) (f)

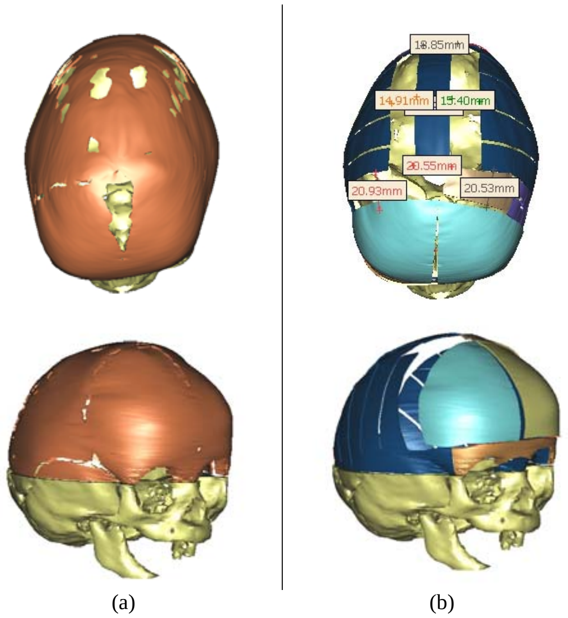
Figure 2: Bone piece outer surface detection and template deduction for the forehead in Matlab®

After outer surface growing (a), the *technician/surgeon* selects on the surface a horizontal cutting plane (b) and a set of vertical cutting planes (c-d). The procedure calculates the intersection curves (d) and the curve lengths, unfolds the three-dimensional template to a two-dimensional printable representation (e) and finally creates a triangulation mesh of the three-dimensional template for visualisation and validation purposes (f).

Finally, the planar representation of the template is printed and copied onto an aluminium or plastic foil. The use of a stereolithographic model (SLA) eventually allows the surgeon to practice the consecutive steps of the surgical intervention and to validate the position and fit of the two-dimensional prints on the skull surface if necessary. Since this seriously increases the cost of the planning procedure it is not preferable. After sterilization, the aluminum copies transfer the surgery planning to the operation room, a cost-efficient solution.

Results

Mesh generation. Figure 1a-b presents a malformed neurocranium of a 5 months old neonatus. On the one hand, a prematurely closed left coronal suture resulted in a flattened forehead on the left and a bulging forehead on the right to compensate the loss in skull volume, also called anterior plagiocephaly. On the other hand the sagittal suture appears to be closed, which indicates the presence of a scaphocephaly. The latter normally results in a saddle-like shape of the head. A pre-operative CT-scan was taken five weeks before scheduled surgery. Starting with 339 bone contours after segmentation, multiple contours were initially allowed in each slice and no small contours were removed. The outer surface stitching procedure proccesed the internal contours, internal loops and small contours at once, by detecting 300 outer contour points in every slice, thereby reducing the number of contours from 339 to 92, which equals the number of slices for the neurocranium. The procedure deleted no little loops, but as much as 803 small triangles representing noise. The interactive correction phase was executed automatically and no manual editing took place. The default imposed accuracy in one point of the splines was set to 1 mm and automatically lowered for the smaller contours. The mean imposed and obtained accuracies of the splines used for the neurocranium outer surface mesh were 0.96 ± 0.09 mm and 0.67 ± 0.18 mm respectively. The mesh, built from 100 points per spline, contains 9149 quadrilaterals. Opening the holes completely removed 457 quadrilaterals, and about twice that number of quadrilaterals were adjusted to generate an accurate suture opening. Both meshes (Figure 1b-c), namely one without and one with sutures, represent only the outer surface of the neurocranium, contain less noise and fit well on the original CT-data of the patient. The uncompiled Matlab® program obtained the mesh in about 20 minutes, from which about five minutes were used for user interactions.



(a) (b)

Figure 3: Resulting surgery planning

The original skull shape before virtual surgery simulation (a) shown by the surface mesh with opened sutures and the skull shape after virtual surgery simulation (b) on the closed mesh model of the neurocranium.

Virtual surgery. An internal offset of 1mm of the closed mesh model made it possible to simulate surgery in the commercial Mimics® environment. The closed left coronal suture was taken out over a width of 20mm and replaced by the contralateral intact suture. In order to fit the intact suture, it was cut in two pieces. The orbital rim was straightened to undo the bulging on the right side. Moreover the forehead was cut into two pieces, which were rotated and translated over small angles and distances, clockwise in top view. To make room for the developing brain and to compensate for the present scaphocephaly, a parasagittal ostectomy of about 15mm width was carried out towards the lambdoid suture. In the left and right parietal zones, the Barrel Stave technique was applied by introducing a large number of radial osteotomies creating bone segments which were to be bended outwards during surgery. The resulting surgery planning is shown in Figure 3.

Template design. After simulating surgery on the created neurocranium mesh, the four osteotomized and three resected bone parts were translated into printable template representations by the procedures described above (Figure 2a-e). A strip width of 5mm was chosen for all templates, except for the smaller orbital rim which required a strip width of 4mm. For validation and visualisation purposes, a template mesh was created for each bone piece (Figure 2f). Validation of the surgery planning and the template position and outline took place on the CT data and on the three-dimensional visualisation in the Mimics® software. After validation by the surgeon, the templates were copied on 0.3 mm thick aluminium foil and cut out.

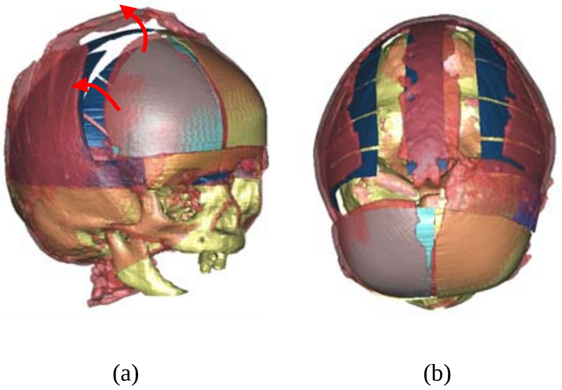
A total time estimate for a skull reconstruction planning, comprising the entire acquisition, filtering, mesh building, surgery planning, template generation, validation and template production, is difficult to assess because of the user and case specificity, which affects the surgery simulation and the number of templates to generate. In the presented case, the mesh and template generation lasted for about one hour in total, excluding the duration of the virtual surgery. Virtual surgery itself took a few days because of trying out some different approaches and the necessary communication between technician and surgeon.

Figure 4: Marking of the bone segment border according to the template

The *surgeon* marks the border of the bone segment by connecting the ends of the strips of the template with a lead pencil.

Surgery. The two-dimensional aluminium templates were autoclaved and transferred to the cranium. Markings were done with an autoclaved soft lead pencil (Figure 4). Firstly, the orbital rim was outlined. This served as a reference for the positioning of the forehead cutting template. The other template positions were built up gradually -with the one before serving as a reference- ending at the back of the head with the parasagittal ostectomy. The Barrel Stave osteotomies were made according to some screenshots of the pre-operative plan, because the position of the incisions did not require the same precision as the bone segments outline. The reconstruction was carried out exactly following plan, except for the positioning of the transplanted intact coronal suture. During surgery, flipping of the bone segment -in stead of cutting- seemed preferable to create the best fit. The osteosynthesis of the frontal bone segments was done with micro 3D plates. The operation lasted 3 hours and 10 minutes.

Post-operative validation. A post-operative CT-scan was taken two weeks after surgery. After quick segmentation and region growing a high quality volume model was generated of the reconstructed skull. This model was matched on the virtual surgery planning by the standard matching tools available in the Mimics® software. Taken the difference due to growth between pre- and post-operative CT-scan into account, the surgery plan was nicely followed, with bone piece accuracies of about 1-2 mm (Figure 5). The parasagittal ostectomy and Barrel Stave osteotomies lead to an enlargement of skull volume due to outward bending. Further more, straightening out of the forehead was performed exactly as planned, which resulted in a good aesthetic result.



(a) (b)

Figure 5: Post-operative result matched on the pre-operative surgery planning in Mimics®

Skull volume enlargement due to ostectomies and Barrel Stave osteotomies (a) and straightening of the forehead according to surgery plan (b).

Discussion

Triangulated vs. analytical representation. As the outer surface mesh itself and all results of the platform-independent procedures have a triangulated representation, they are directly interchangeable with digital CAD and rapid prototyping software [3Matic®, Magics®, SolidView®, 3DLightyear®, FlashTLEngineer®], with the associated advantages of straightforward design and production. For comparison, analytical representations in regular CAD packages, such as NURBS surfaces, are not easy to control, encounter branching problems, sometimes inhibit straightforward CAD operations, and are problematic in case of irregular but anatomically correct bone shapes as the surface would wrinkle [16].

Surface vs. volume representation. Surgery simulation starts from an outer surface STL representation of the neurocranium and does not use a full volume STL model representation of the skull, even though such volume STL could easily be generated directly in the Mimics® environment by means of a Marching Cubes algorithm [17]. Nonetheless, for the presented applications, the outer surface presentation has some innovating advantages over a volume model.

Firstly, compared to a high resolution volume STL, an outer surface STL offers similar quality and accuracy of representation for a much smaller dataset. A high resolution volume STL of the neurocranium in the presented case, created by the standard Mimics® tools, contains 279,764 triangles, about 16 times the number of triangles in the surface mesh created by the above mentioned procedures. A rather inaccurate low quality volume model still contains 42,568 triangles, about 2.5 times the number of triangles in the surface mesh.

Secondly, template deduction is *in se* completely surface based, meaning that redundant information such as inner contours and internal loops must be removed in order not to tangle automated procedures which directly retract information from the visualisation mesh. The automated filter sequence was implemented to retrieve an outer bone surface, as it could not be obtained from a largest shell extraction from an unfiltered volume STL. Moreover, the filters inherently prohibit the polylines from penetrating the bone, and the splines are calculated to a controllable accuracy.

Thirdly, a small dataset renders faster, handles easier and is more straightforward in surgery simulation. Depth estimates of osteotomies to make sure that the bone is completely cut through are unnecessary for a thin outer bone shell. When the developments will be extended to bone piece bending - a typical feature often needed in cranial reconstructions and part of future work - thickness information of the bone for mechanical analysis can be saved in the background.

And fourthly, the implemented procedures have the ability to return to their ‘roots’, namely the bone contour representation. Contours can be adapted for reconstructions such as loop removal, reshaped to obtain smooth transitions with other contour sets, analysed for suture openings etc. Furthermore, a designer can easily switch between the STL mesh and the contour representation; a spline set is easily converted to an outer surface mesh and an outer surface mesh can be swiftly resliced into a reoriented contour set. Further research will certainly exploit these advantages.

Transfer to the operation room. The final step after surgery simulation, transfer to the operation room, can be achieved by different techniques. Besides the templates presented here, navigation systems and robot-guided surgery are the two most common methods [3][13][14]. Both of them mostly facilitate surgical tasks which require high precision, whereas human precision is satisfactory in the presented application. Moreover these systems are expensive and besides safety aspects, which are extremely important in robot-guided surgery, the used planning environment needs to be adapted to become an integrated system. Each step in the planned surgery has to be divided in elementary operations which can be performed by a robot [13]. Moreover, concerning the generation of a three-dimensional representation of the skull, it must be reminded that the trajectory of a robot is defined by a set of spatial coordinates or splines.

Only recently authors more often mention the use of templates or surgical guides to transfer the surgical plan to the operation room [18]. This technique is mostly used in dental applications [19][20] ; in craniofacial applications it is still exceptional. Two possible approaches are common for craniofacial surgery: aluminium [18][21] and stereolithographic templates [22]. The most obvious advantage of the former is the cost-efficiency. Moreover this paper presents a semi-automatic and relatively quick procedure to deduce the surface based templates which are easy to produce. The general idea was introduced by Jans *et al*. by means of a NURBS based CAD planning environment for craniofacial surgery [2][21]. The template design presented here offers some extra advantages: it is planning environment independent, interchangeable with digital CAD software and deals with either volume representations as well as surface representations of the bone segments.

Template layout. Because the template consists of small vertical and horizontal strips it is easily bendable along the bone surface. A semi-automatic template generation – the user selects the position of the strips on the bone piece - allows significant edge parts to be incorporated into the ends of the strips. Moreover, the templates are adjustable to larger or smaller bone pieces since the user can determine the strip width and the number of vertical strips. Although the fact that thin aluminium foil implicates careful handling and that only small parts of the bone piece outline are available to delineate the entire outline on the skull, an efficient transfer of the operation planning to the patient’s neurocranium is achieved by use of the templates in combination with simulation screenshots and pre-operative distance measurements.

Conclusions

One general and thorough main filter procedure allows using the necessary filter modules, depending on the type of bone and malformation, to create an easy to handle outer bone surface mesh, available in STL file format. With the filter and mesh implementations as base platform, a simple, straightforward and planning-environment-independant solution is generated for a complex practical problem like surgery planning transfer to the operation room. The transfer of a cranial reconstruction surgery planning is cost-efficiently established by creating surface based templates for the different osteotomized bone pieces. A succesful clinical case illustrated the feasibility of the above-mentioned developments.

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References

[1] PAPPAS P.I., TESCHNER M., CHAPUIS J. and CAVERSACCIO M. (2003): 'Technical challenges in computer-aided cranio-maxillofacial and reconstructive surgery', *Inproc. of CAS-H 2003 – Computer Aided Surgery around the Head*, 2003, p. 1.

[2] MOMMAERTS M., JANS G., VANDER SLOTEN J., STAELS P.F., VAN DER PERRE G. and GOBIN R. (2001): 'On the assets of CAD planning for craniosynostosis surgery', *Journal of Craniofacial Surgery*, 12(6), pp. 547-554

[3] GIROD S., TESCHNER M., SCHRELL U., KEVEKORDES B. and GIROD B. (2001): 'Computer- aided 3-D simulation and prediction of craniofacial surgery: a new approach', *Journal of Maxillofacial Surgery*, 29(3), pp. 156-158

[4] CUTTING C., GRAYSON B., BOOKSTEIN F., FELLINGHAM L. and MCCARTHY J.G. (1986): 'Computer-aided planning and evaluation of facial and orthognatic surgery', *Clinics in Plastic Surgery*, 13, pp. 449-462

[5] KASS M., WITKIN A. and TERZOPOULOS D. (1987): 'Snakes: active contour models', *Int. J. Computer Vision*, 1(4), pp. 321-331

[6] COOTES T.F., TAYLOR C.J., COOPER D.H. and GRAHAM J. (1995): 'Active shape models – Their training and application', *Computer Vision and Image Understanding*, 61(1), pp. 38-59

[7] KAUS M.R., LORENZ C., TRUYEN R., LOBREGT S and WEESE J. (2003): 'Automated 3D PDM construction from segmented images using deformable model', *IEEE Transactions on Medical Imaging*, 22(8), pp. 1005-1013

[8] RAJAMANI K.T., JOSHI S.C. and STYNER M.A.. (2004): 'Bone model morphing for enhanced surgical visualization', *Proc. of IEEE International Symposium on Biomedical Imaging*, 2004, p. 1255-1258

[9] STYNER M.A., RAJAMANI K.T., NOLTE L-P., ZSEMLYE G., SZÉKELY G., TAYLOR C.J. and DAVIES R.H. (2004): 'Evaluation of 3D correspondence methods for model building', *Proc. of Information Processing In Medical Imaging*, 2003, p. 63-75

[10] ALTOBELLI D.E., KIKINIS R., MULLIKEN J.B., CLINE H., LORENSEN W. and JOLESZ F. (1993): 'Computer-assisted three-dimensional planning in craniofacial surgery', *Plastic and Reconstructive Surgery*, 92, pp. 576-587

[11] LO L.J., MARSH J.L.., VANNIER M.W. and PATEL V.V. (1994): 'Craniofacial computer-assisted surgical planning and simulation', *Clinics in Plastic Surgery*, 21, pp. 501-516

[12] CUTTING C., BOOKSTEIN F.L, GRAYSON B., FELLINGHAM L. and MCCARTHY J.G. (1986): 'Three-dimensional computer-assisted design of craniofacial surgical procedures: optimization and interaction with cephalometric and CT-based models', *Plastic and Reconstructive Surgery*, 77, pp. 877-887

[13] BOHNER P., HOLLER C. and HASSFELD S. (1997): 'Operation planning in craniomaxillofacial surgery', *Computer Aided Surgery*, 2, pp. 153-161

[14] HASSFELD S. and MÜHLING J. (2001): 'Computer assisted oral and maxillofacial surgery – a review and an assessment of technology', *International Journal of Oral and Maxillofacial Surgery*, 30, pp. 2-13

[15] GELAUDE F., VANDER SLOTEN J. and LAUWERS B. (2005): 'Semi-automated segmentation and visualisation of outer bone cortex from medical images', *submitted to Comp. Meth. In Biomech. And Biom. Eng.*

[16] GELAUDE F., PATTIJN V., VANDER SLOTEN J. and VAN AUDEKERCKE R. (2003): 'Simulation and Biomechanical evaluation of reconstructive surgery of the hip in children', *Proc. of Belgian Day On Biomedical Engineering 2003*, 2003, p. 52

[17] LORENSEN W.E. and CLINE C.H. (1987): 'Marching Cubes: A High Resolution 3D Surface Construction Algorithm', *Computer Graphics*, 21(4), pp. 163-169

[18] EUFINGER H., WITTKAMPF A.R., SCHRAMM A., WEIHE S., RASCHE C. and WEHMÖLLER M. (2001): 'The use of individual surgical templates in computer assisted surgery', *Inproc. of CARS 2001 – The 15th International Congress of Computer Assisted Radiology and Surgery*, 2001, p. 224-228

[19] BLANCHET E., LUCCHINI J.P., JENNY R. and FORTIN T. (2004): 'An image-guided system based on custom templates: case reports', *Journal of Craniofacial Surgery*, 6(1), pp. 40-47

[20] SAMMARTINO G., DELLA VALLE A., MARENZI G., GERBINO S., MARTORELLI M., DI LAURO A.E. and DI LAURO F. (2004): 'Stereolithography in oral implantology: a comparison of surgical guides', *Implant Dent.*, 13(2), pp. 133-139

[21] JANS G., VANDER SLOTEN J., GOBIN R., VAN DER PERRE G., CAN AUDEKERCKE R. and MOMMAERTS M. (1999): 'Computer-aided craniofacial surgical planning implemented in CAD software', *Computer Aided Surgery* , 4, pp. 117-128

[22] SCHUTYSER F., VAN CLEYNENBREUGEL J., NADJMI N., SCHOENAERS J. and SUETENS P. (2000): '3D image-based planning for unilateral mandibular distraction', *Proc. of CARS 2000, The 14th International Congress of Computer Assisted Radiology and Surgery*, 2000, p. 899-904