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# 3D digital geometry designs for Poland's syndrome using Magics and Geomagic® Freeform®

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**Abstract**

**Purpose** – Poland's syndrome patients often seek medical interventions to improve their aesthetic appearances. Design and manufacturing technologies make it possible to produce custom-made implants for such medical conditions. The purpose of this study was to compare the 3D digital geometries that were designed using Magics and Geomagic® Freeform® for two anonymous case studies of Poland's syndrome patients.

**Design/methodology/approach** – Computed tomography data were acquired and processed in Mimics® to isolate the pectoralis muscles in STL file format. STL files were imported into Magics and Geomagic® Freeform® to design 3D digital geometries. Thereafter, comparative analyses were performed of the respective 3D digital geometries.

**Findings** – The angle between the vertical and oblique planes for both sides of the thorax was 6.5° for the female and 14° for the male. The surface areas and volumes of the geometries for the female were smaller than the male. Deviation analyses between the healthy side and reconstructed side of a thorax showed that 73 per cent of the test points for Magics and 78 per cent for Geomagic® Freeform® fell in the nominated tolerance region of $>-5$ and $<+5$ mm for the female. For the male, it was 83 per cent for Magics and 88 per cent for Geomagic® Freeform®.

**Practical implications** – Geomagic® Freeform® provides a more versatile design environment; however, the STL editor Magics may be an option to design 3D geometries for less intricate and less contoured implants.

**Originality/value** – This was a first attempt to compare the 3D geometries for Poland's syndrome designed with an STL editor to those designed with a computer-aided design program.

**Keywords** Computer-aided design, 3D digital geometry, Medical imaging technology, Medical modelling, Poland' syndrome, Soft tissue

**Paper type** Research paper

## 1. Introduction

Poland's syndrome is a unilateral congenital defect displaying a wide variety of deformities, mostly of soft tissues and the skeleton (Dustagheer *et al.*, 2009; Gashegu *et al.*, 2009; Baltayiannis *et al.*, 2011; Majdak-Paredes *et al.*, 2015). The severity of the deformities in patients vary from person to person; however, all the manifestations of the syndrome are rarely simultaneously present in one individual (Pereira *et al.*, 2008; Urschel, 2009; Lee *et al.*, 2012; Al Faleh *et al.*, 2014). The syndrome commonly affects the right side of the thorax and is more often found in males (Kamburoğlu *et al.*, 2011; Chen *et al.*, 2012; Stylianos *et al.*, 2012; Caouette-Laberge and Borsuk, 2013; Chowdhury *et al.*, 2015). Many patients display the absence of the pectoralis major muscle, although other muscles such as the pectoralis minor may also be affected (Poland, 1841; Lacorte *et al.*, 2010). Poland's syndrome is also often associated with hand deformities of varying severities (Mentzel *et al.*, 2002; Ersen *et al.*, 2015).

Individuals affected by Poland's syndrome usually seek some or other medical intervention to improve their aesthetic appearance (Mathes *et al.*, 2005; Pereira *et al.*, 2008; Yadav *et al.*, 2014), although full correction of the asymmetry is unattainable due to the complexity of the syndrome (Majdak-Paredes *et al.*, 2015). Most of the interventions involve some or other surgical reconstruction, which is often invasive in nature requiring extended recovery times and may be rather traumatic for the patient (Urschel, 2009). There is a constant search for less-invasive and less-traumatic approaches to the reconstruction of Poland's syndrome deformities.

Surgically inserted prosthetic implants have evolved as successful alternatives to reconstruct chest wall deformities such as for Poland's syndrome (Saour *et al.*, 2008). The production of prosthetic implants has been accomplished using many different techniques. The conventional carving

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techniques for fabricating wax models are difficult, time-consuming and cause discomfort to patients (Feng *et al.*, 2010). With the advances in medical modelling and the accompanying development of medical imaging, design and manufacturing technologies, it has become possible to produce custom-made prosthetic implants for more complex medical conditions. The use of digital design options for designing and developing custom-made prosthetic implants for the reconstruction of Poland's syndrome deformities is an attractive alternative to invasive surgery. This alternative approach is less-invasive and requires less-extensive recovery times than the more invasive surgical procedures (Costa and Blotta, 2012).

The major features of the process chain for the development of digitally designed prosthetic implants comprises the capture of digital data, the design of 3D digital geometries and finally the production of implants through additive manufacturing (AM). Although there are different AM building technologies, most of them consist of adding material layer-by-layer until a desired shape is built (Pinto *et al.*, 2015). The main differences between different AM building technologies lie in the way layers are deposited to create a shape and in the materials that are used. Polymers are the most widely used materials for the manufacturing of biomedical devices, including soft-tissue. Some polymers are natural materials, such as cellulose, natural rubber and collagen, whereas synthetically fabricated materials such as polyethylene, polypropylene, polyethylene terephthalate, polyethylene glycol and polyetheretherketone are also used (Nag and Banerjee, 2012; De Leon *et al.*, 2016). Prosthetic implants are generally manufactured from 3D digital geometrical designs using biocompatible materials. Such implants may be manufactured directly or through mould tools (Saour *et al.*, 2008). However, with the recent development of an integrated tissue-organ printer, it is now possible to manufacture human-scale soft tissue constructs of any shape through cell-laden hydrogels together with biodegradable polymers (Kang *et al.*, 2016).

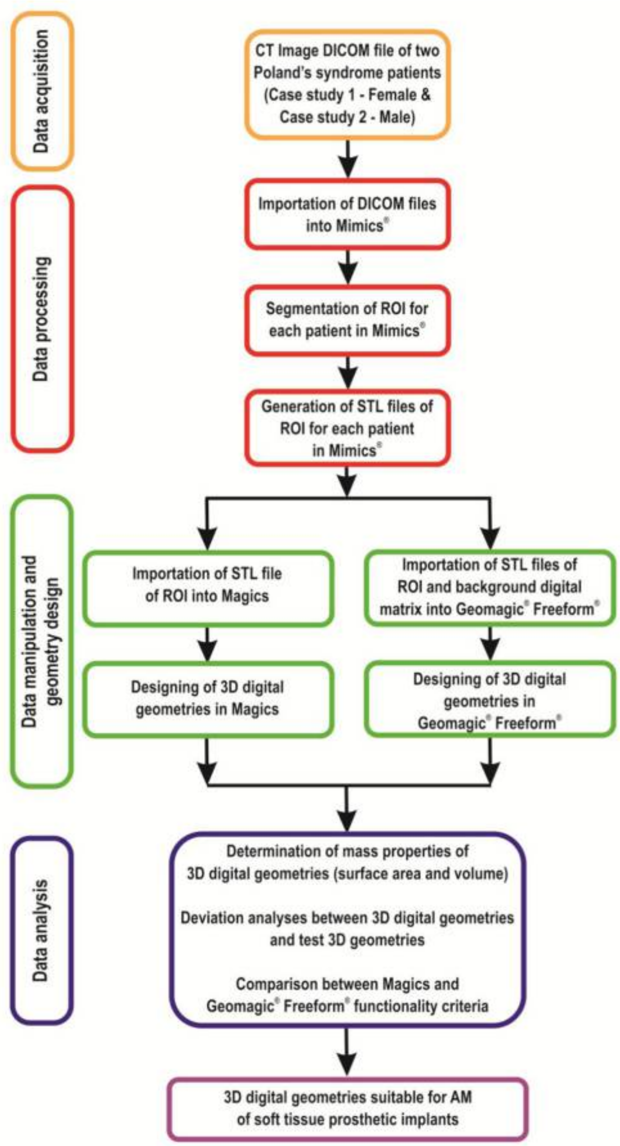
Successful digitally designed prosthetic implants are dependent on the accuracy of the digital data and the 3D digital geometrical designs. Digital data capturing techniques, such as computed tomography (CT) and magnetic resonance imaging, have the advantage of using digital scan data that provides pre-operative insight into the pathogenesis of the body through the capturing of accurate medical digital data (Petrovic *et al.*, 2012). Various software programs are used in the digital design process to manipulate the captured digital data to produce 3D digital geometries that can be used in the production of custom-made prosthetic implants through AM (Saour *et al.*, 2008).

In the past, the program Magics (Materialise® N.V, Technologielaan 15, 3001 Leuven, Belgium) was exclusively used at the institute where this study was conducted for the development of medical geometries for soft tissue implants (Truscott *et al.*, 2012). With the inception of this project, the software program Geomagic® Freeform® (333 Three D Systems, Circle Rock Hill, SC 29730, USA) was purchased for design purposes of all types of models, including medical models. Magics software has two main characteristics; firstly, it is used as an STL editor, and secondly, it is used to prepare 3D digital geometry models for the AM process. On the other hand, Geomagic® Freeform® is a computer-aided design (CAD) software program that allows sculpting capabilities in a digital 3D virtual space, as well as advanced features of 3D CAD modelling. The sculpting capabilities in a virtual space are provided by the sense of touch of a haptic device, which is combined with Geomagic® Freeform®. The stylus arm of the haptic device is used to manipulate solid, complex, shapes and forms. A solid model can be grounded away, stretched, pushed or added in a manner comparable to sculpting with clay (Eggbeer, 2008). Therefore, the purpose of this study was to compare 3D digital geometries that were designed using Magics and Geomagic® Freeform® of missing pectoralis muscles for two anonymous Poland's syndrome patients (Case studies 1 and 2). The resultant 3D digital geometries can be used for AM of soft tissue implants for these patients.

## 2. Design methodology

The 3D digital geometry design workflow of this project comprised four operational steps as shown in Figure 1. These

**Figure 1** Proposed design workflow for the design of soft tissue 3D digital geometries



steps included data acquisition, data processing, data manipulation and 3D digital geometry design using Magics and Geomagic® Freeform®, as well as a comparative analysis of the 3D geometries produced in both the software programs.

### 2.1 Data acquisition

Anonymous CT imaging data sets of the two Poland's syndrome patients were acquired in Digital Imaging and Communications in Medicine file format (DICOM file format). One data set was of a female, referred to as Case study 1, and the other of a male referred to as Case study 2. The female patient was missing the pectoralis major muscle on the right side of thorax, whereas it appeared as if the male patient was missing the pectoralis major and minor muscles, also on the right side of the thorax. The number of CT scan slices for Case study 1 was substantially less (152) than those for Case study 2 (533). The CT scan slice thickness (2 mm) and slice increment (2 mm) of Case study 1 were of equal size and non-overlapping. In contrast, the slice increment (0.7 mm) for Case study 2 was smaller than the slice thickness (1 mm), thus producing overlapping CT scan slices. The resolution (pixels) for both cases was 512 × 512, whereas the pixel size for Case study 1 was 0.883 mm, and for Case study 2, it was 0.779 mm.

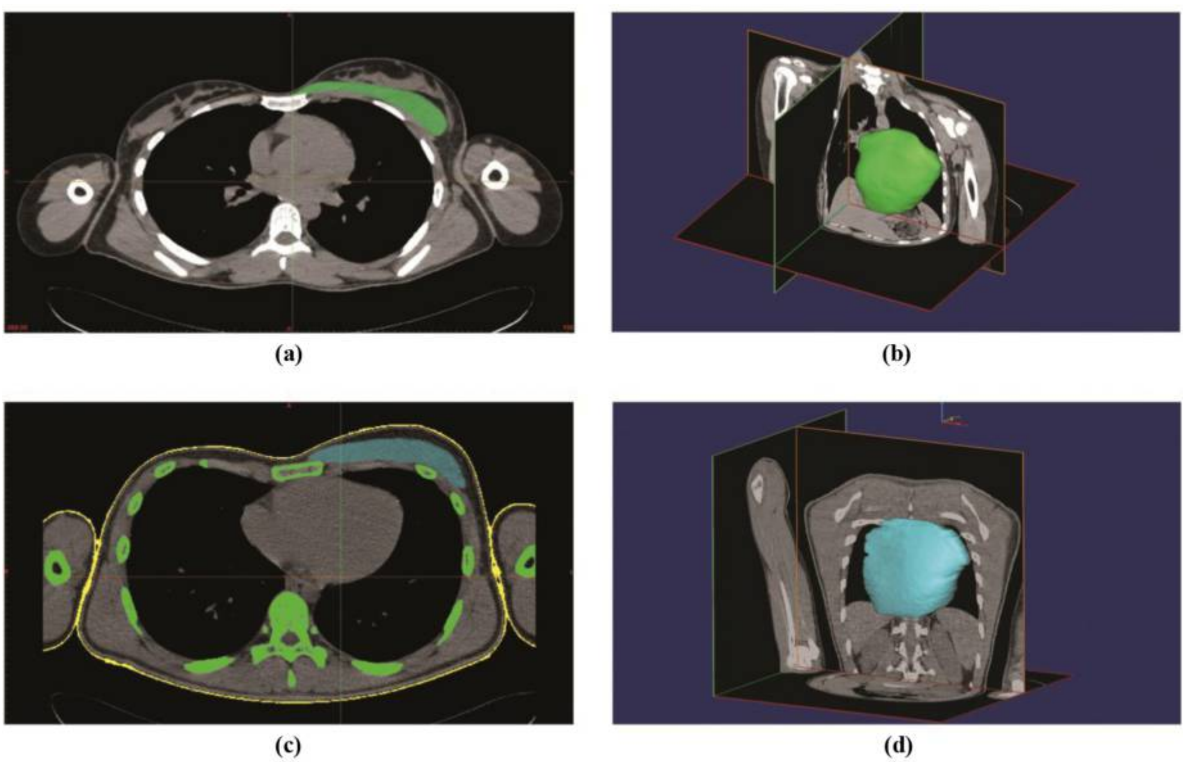
### 2.2 Data processing in Mimics®

The DICOM files of the CT data sets of the two Poland's syndrome patients were imported into Mimics® software (Materialise® N.V, Technologielaan 15, 3001 Leuven, Belgium). These data sets were then processed to create 3D digital geometries of the contralateral soft tissues in the left, healthy side of the thoraxes. These contralateral soft tissues were referred to as regions of interest (ROI). The processing involved a number of manipulations and pixel-by-pixel editing steps to isolate the ROI. The segmentation functions of Mimics® were applied to highlight and remove all unwanted anatomical digital data from the ROI using segmentation masks with an appropriate threshold. The 3D digital geometries of the ROI were obtained by the region growing techniques of Mimics®, which involved the editing and refining of the segmentation masks to ultimately calculate and produce the 3D digital geometries of the ROI in STL file format. After the segmentation of the ROI of the two case studies, the thorax of each patient was also digitally processed to produce STL files, which was necessary for the 3D geometry design in Geomagic® Freeform®.

### 2.3 Data manipulation and 3D geometry design

The STL files of the segmented ROI produced in Mimics® were imported into Magics. The design of the 3D digital geometries for the deformed right side of the thorax of the two case studies entailed the activation of coordinate planes and then the production of mirror images of each of the segmented ROI. For the design of the 3D digital geometries in Geomagic® Freeform®, the STL files of the segmented ROI, as well as the thorax of each case study were imported. The thoraxes acted as reference pieces by providing a background digital matrix

**Figure 2** Segmented ROI




**Notes:** (a) ROI of Case study 1 indicated in green; (b) segmented ROI of Case study 1 presented in 3D; (c) ROI of Case study 2 indicated in blue; (d) segmented ROI of Case study 2 presented in 3D

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displaying the affected region into which the designed 3D digital geometries could be projected and fitted. Similar to Magics, the coordinate planes of Geomagic® Freeform® were activated. A number boundary curves were drawn and fitted on the healthy halves of the thorax reference pieces. Thereafter, the boundary curves were individually mirrored onto the affected half of each thorax, prior to importing the segmented ROI into their original localities in the left side of thorax reference pieces. The segmented ROI were then mirrored into the deformed right side of the thorax reference pieces. Finally, the mirrored, segmented ROI were manipulated using the tug tool and the sculpting capabilities of the haptic device to fill the space beneath the boundary curves to produce the 3D digital geometry designs of the missing soft tissue.

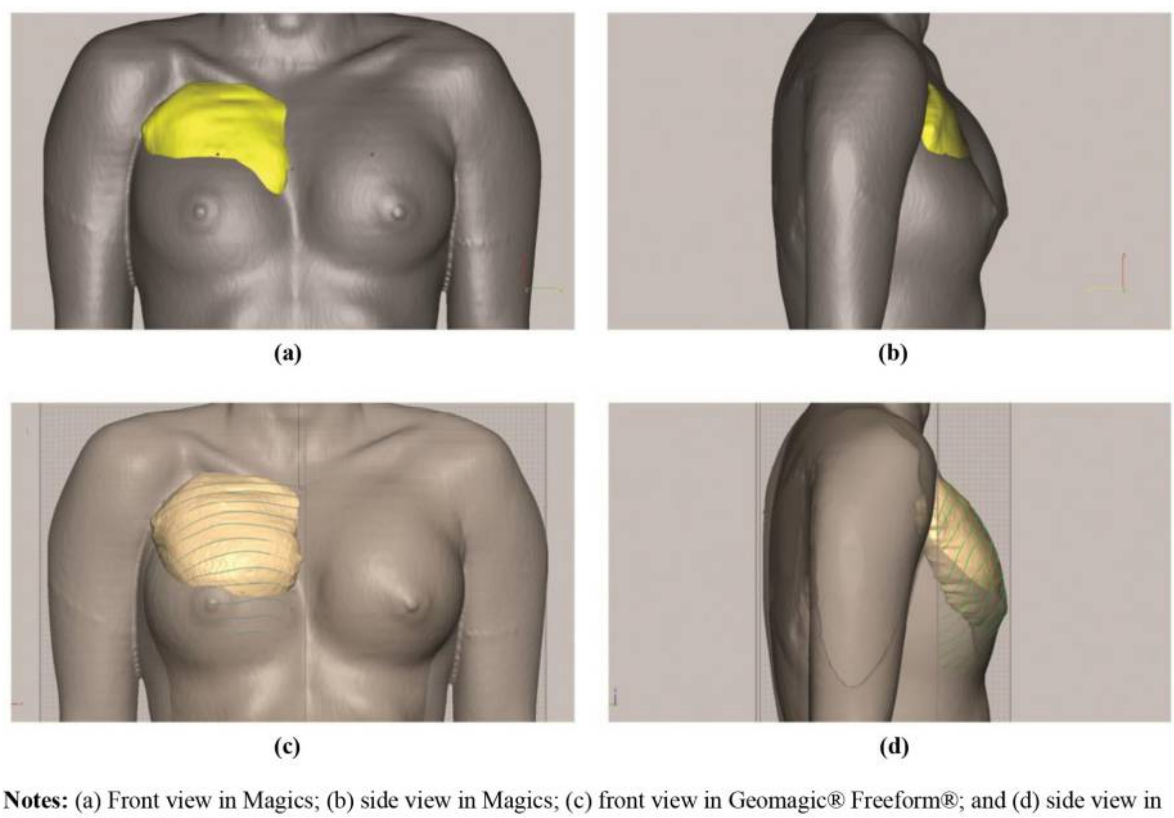
### 2.4 Comparative analyses of Case studies 1 and 2

To demonstrate to what extent the deformities of the two case studies had resulted in an asymmetrical body type of the thorax, Geomagic® Freeform® was used to indicate the difference between the healthy and affected sides of the thorax for both two case studies. A vertical plane touching the shoulder was inserted together with an oblique plane stretching from the shoulder to the upper contour of a breast. The angle between the vertical and the oblique planes was determined for each half of the thorax. Thereafter, the difference between the two angles was calculated.

Two comparative strategies were followed to compare the 3D digital geometries designed in Magics and Geomagic® Freeform®. Firstly, the mass properties, surface area and volume of the designed 3D digital geometries were determined using Geomagic® Freeform® for both case studies and compared. Secondly, deviation analyses were performed between each of the designed 3D digital geometries and a specific test 3D geometry using Geomagic® Control™. Separate test 3D geometries were created for each case study. A test 3D geometry was created by firstly joining a designed 3D digital geometry in the right, deformed side of the original STL file of the thorax. This produced a representation of a reconstructed body conformation. Thereafter, the reconstructed thorax was mirrored. This mirrored reconstructed thorax was then superimposed onto the reconstructed thorax by aligning as many body contour points as possible. This resulted in the superimposition of a healthy half of a thorax onto a reconstructed half of a thorax. A deviation analysis was then performed between these two halves.

To perform the deviation analyses, a tolerance interval was nominated. For this study, the nominated tolerance interval was set at ≥−5 mm and ≤+5 mm, taking into consideration the differences of female and male mammary soft tissue and fat deposition (recommended by a medical practitioner). Two regions beyond the nominated interval were also defined. The critical plus interval showed data points where the designed 3D digital geometries were larger than the test 3D geometries, whereas the critical minus interval showed data points where the designed 3D digital geometries were smaller than the test

**Figure 3** Designed 3D digital geometries of Case study 1



**Notes:** (a) Front view in Magics; (b) side view in Magics; (c) front view in Geomagic® Freeform®; and (d) side view in Geomagic® Freeform®

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3D geometries. The critical plus interval was defined as the interval from >5 to <50 mm, whereas critical minus interval was defined as the interval from >−50 to <−5 mm.

Although an in-depth assessment of the designing capabilities of Magics and Geomagic® Freeform® was not the focus of this study, an attempt was made to compare the designing process of the two programs. A list of criteria was composed describing the different designing attributes that were used to compare the programs.

## 3. Results of case studies

### 3.1 3D digital geometry design

Segmentation in Mimics® produced 3D digital geometries of the ROI for each case study. Figure 2 indicates the segmented ROI in the healthy half of the thorax for Case study 1 [Figure 2(a)] and Case study 2 [Figure 2(c)]. A 3D rendition of each of the ROI is displayed in Figure 2(b) and (d).

For both case studies the Magics 3D digital geometries were simply mirror images of the segmented ROI, because manipulation of data is limited in Magics. For Case study 1, the 3D digital geometry produced using Geomagic® Freeform® was manipulated by tugging and sculpting with the haptic device using boundary curves as a guide. This resulted in the 3D digital geometry filling the space more effectively and producing a more aesthetic outcome (Figure 3). For Case study 2, the 3D digital geometry designed using Geomagic® Freeform® produced a similar aesthetic outcome as the 3D digital geometry designed in Magics, requiring less tugging and sculpting than for Case study 1 (Figure 4).

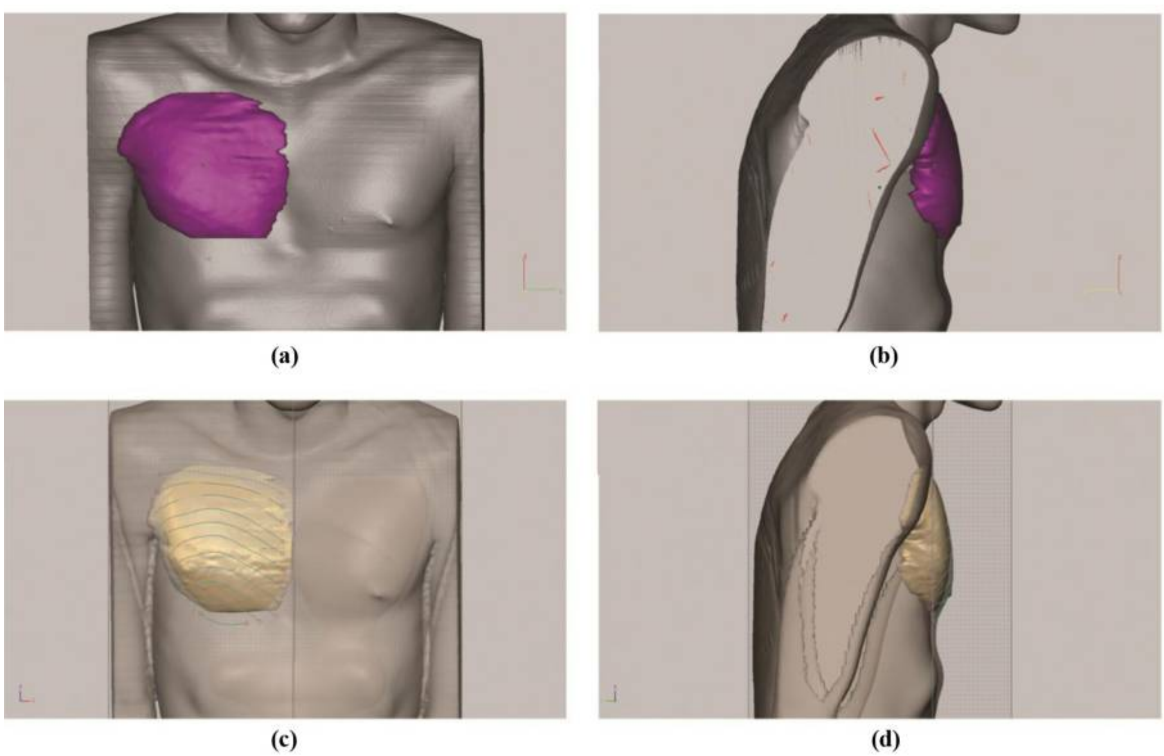
### 3.2 Comparative analysis of the soft tissue geometries and software

The extent of the asymmetrical body type of Case study 1 was less than that of Case study 2. The difference between the two halves of the thorax of Case study 1 was 6.5° (33°-26.5° = 6.5°), whereas that of Case study 2 was 14° (17°-3° = 14°) (Figure 5). These angles indicated that the space to be filled by an implant was larger for Case study 2, when compared to Case study 1.

The mass properties of the designed 3D digital geometries revealed that the geometrical designs for the two case studies differed substantially in surface area and volume. The surface areas and volumes of the 3D digital geometries for Case study 1 were smaller when compared to those designed for Case study 2, supporting the notion that the space to be filled in Case study 2 was greater than that of Case study 1 (Table I). Because of the availability of the tug and rotate tools in Geomagic® Freeform®, the design process was facilitated to produce better fitting and larger 3D digital geometries in both case studies. This was reflected in the larger surface areas and volumes of the geometries designed in Geomagic® Freeform® when compared to those designed in Magics.

Geomagic® Control™, which was used to calculate the deviations between a healthy side of the thorax and a reconstructed side of the thorax allocated for Case study 1 approximately three times more test points for the 3D digital

**Figure 4** Designed 3D digital geometries of Case study 2



**Notes:** (a) Front view in Magics; (b) side view in Magics; (c) front view in Geomagic® Freeform®; and (d) side view in Geomagic® Freeform®

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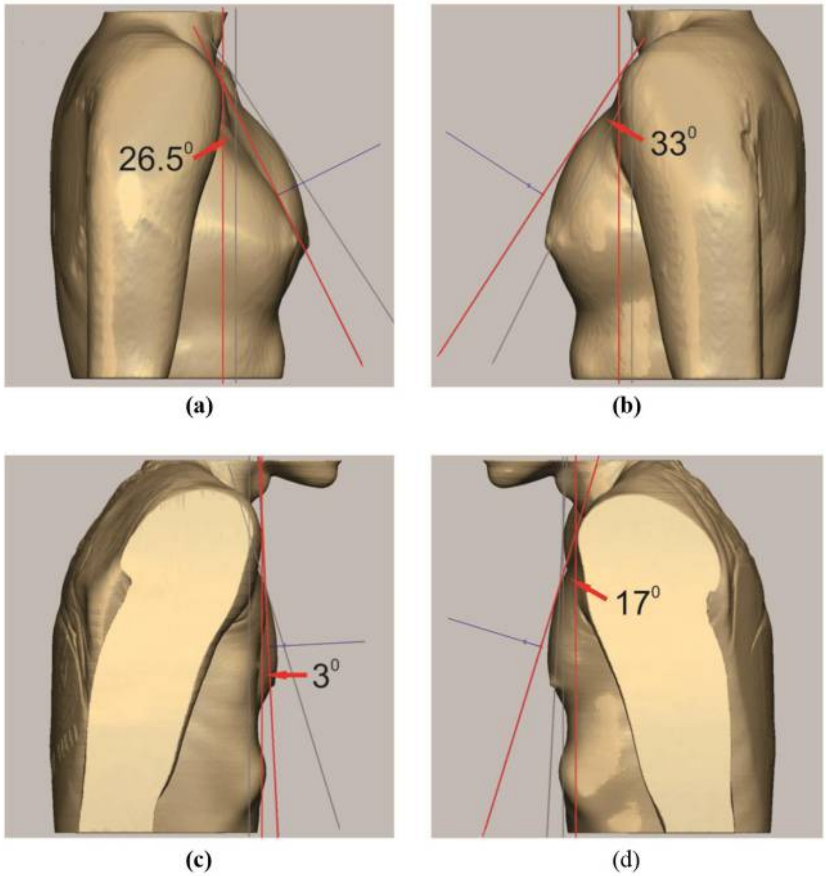
**Figure 5** Angles between vertical and the oblique planes are indicated in red




**Notes:** For Case study 1: (a) left view of the thorax showing the vertical and oblique plane of the affected side and (b) right view of the thorax showing the vertical and oblique plane of the healthy side. For Case study 2: (c) left view of the thorax showing the vertical and oblique plane of the affected side and (d) right view of the thorax showing the vertical and oblique plane of the healthy side



**Table I** Mass properties of the 3D digital geometry designs of the ROI

| | Software used to design 3D digital geometry | | | |
|---|---|---|---|---|
| Mass property | Magics *Case study 1* | Geomagic® Freeform® *Case study 1* | Magics *Case study 2* | Geomagic® Freeform® *Case study 2* |
| Surface area × $10^3$ ($mm^2$) | 34.5 | 42.1 | 50.3 | 53.6 |
| Volume × $10^4$ ($mm^3$) | 16.8 | 19.5 | 34.9 | 36.2 |

geometry designed in Geomagic® Freeform® than for the one designed in Magics. In contrast, for Case study 2, the program allocated 11 times more test points for the 3D digital geometry designed in Geomagic® Freeform® than for the one designed in Magics (Table II). For both case studies the percentage of deviation test points that fell within the nominated tolerance region of ≥−5 and ≤+5 mm was high. Although many more test points were allocated for the geometries designed in Geomagic® Freeform®, the percentage of deviation test points that fell within the nominated tolerance region for the Magics geometries was marginally less than those allocated for Geomagic® Freeform® geometries; in the order of 5 per cent for both case studies. The critical minus interval (≥−50 to <−5 mm) contained the next most number of deviation test points; ranging from 10 to 30 per cent. The critical plus interval (>5 to ≤50 mm) contained less than 2 per cent of the deviation test points, showing that at only a few of the test points the designed geometries were larger than the test 3D geometries.

When comparing the designing capabilities of Magics and Geomagic® Freeform® using the design process criteria, Geomagic® Freeform® outperformed Magics in all the criteria. Table III lists the respective criteria and a comparison of the two programs.

## 4. Discussion and conclusion

Geometrical digital design and accompanying AM technologies are fast becoming major role players in the production of custom-made prosthetic implants for more complex medical conditions. The major advantages of geometrical digital design include the capturing of enough digital data that allows a

**Table II** Percentage data points in the tolerance intervals for Case study 1 and 2

| Deviation analysis criterion | Software used to design 3D digital geometry | | | |
|---|---|---|---|---|
| | Magics *Case study 1* | Geomagic® Freeform® *Case study 1* | Magics *Case study 2* | Geomagic® Freeform® *Case study 2* |
| Number of data points | 64,729 | 184,957 | 47,804 | 525,131 |
| % (number) data points in the nominated tolerance interval | 73 (47,119) | 78 (144,658) | 83 (39,861) | 88 (463,566) |
| % (number) data points in the critical minus tolerance interval | 27 (17,568) | 21 (38,866) | 15 (7,094) | 10 (54,835) |
| % (number) data points in the critical plus tolerance interval | 0.070 (42) | 0.800 (1,433) | 1.8 (849) | 1.3 (6,730) |
| SD | 5.32 | 7.22 | 5.28 | 3.75 |

**Table III** Comparison of the design software programs using software functionality criteria

| Criterion | Description | Design software Magics | Geomagic® Freeform® |
|---|---|---|---|
| Ease of user software interaction | The program is relatively easy to learn and to apply the diverse range of design tools effectively by an experienced software user | Yes | Yes (some elements pose some difficulty) |
| Scope of design tools and tool options | The program allows the user to select from a variety of tools with a relatively large range of options | Few | Many |
| Availability of multiple display views | The program can display a model from multiple angles simultaneously | No | Yes |
| Versatility of order of workflow | The program allows the user to change and select the order of the workflow | No | Yes |
| Possibility of fine refinement of a geometry | The program allows the user to refine geometries with design and sculpting tools | Minimal | Yes |
| Availability of a high-level sculpting device (haptic device) | The program allows for the attachment of a haptic device which creates a virtual environment of "touching" virtual objects with which the user can interact with | No | Yes |
| Development time | The time that the user takes to design a 3D digital geometry for export for manufacturing purposes | Relatively fast | Relatively slower because of more design steps |

designer to design digital geometries with minimal patient involvement (Harih and Čretnik, 2013), the option of remodelling a digital geometry with relative ease, and the ability to store the digital data of a medical model. The 3D digital geometries that were produced for the two Poland's syndrome case studies using Magics and Geomagic® Freeform® turned out to be relatively similar when comparing the different dimensions and deviation analyses. However, Geomagic® Freeform® did demonstrate some advantages over Magics. The haptic device and the range of sculpting tools of Geomagic® Freeform® made it possible to design better fitting 3D digital geometries for the two patients by tugging and pulling, thus producing slightly larger 3D digital geometries when compared to those produced in Magics. The better fitting 3D digital geometries produced in Geomagic® Freeform® was also supported by the deviation analyses that showed a slightly larger percentage of data points that fell within the nominated tolerance interval when compared to those designed in Magics. Other advantages include the wide range of viewing angles and a variety of virtual sculpting and modelling tools (Bibb *et al.*, 2010). However, Magics may be an attractive option in instances where design geometries are required for implants with relatively smooth and less intricate contours and when shorter development times are required.

Soft tissue digital implant design and the AM of implants for complex medical conditions such as Poland's syndrome are still in its infancy. Knowledge about an acceptable tolerance interval for implants that are inserted directly underneath the skin is limited. Research is necessary to define a range of tolerances that will allow analyses of soft tissue implants prior to insertion so that the reconstruction will result in an aesthetic outcome with smooth edges.

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