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Additive Manufactured Models of Fetuses Built from 3D Ultrasound, Magnetic Resonance Imaging and Computed Tomography Scan Data

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1. Introduction

The importance of additive manufacturing (AM) in the biomedical sector has been increasing steadily during the past decade. Different uses of AM models have been reported widely in the medical scientific literature. This study introduces the use of digital generated didactic models into fetal medicine, an area where little work has so far been done in relation to digital 3D modeling. The project proposes a new form of interaction with the idea of the unborn child during the pregnancy, through physically recreating the interior of the womb during gestation: the physical appearance, the actual size, and sometimes also the unexpected event of malformation.

Nowadays, scientific and technological developments in the field of medical imaging scanning and automated interpretation of imagery are having an increasingly significant role in healthcare in order to achieve earlier diagnosis through advanced non-invasive procedures. This integration between medical non invasive imaging systems and additive manufacturing technologies is currently a very promising area covering a wide range of medical imaging modalities, and several researches are being carried out, from the high advances in tissue engineering, to the production of customized implants. Since different uses have been reported widely in the medical literature but little has been published on its application to the gravid uterus, so we applied AM technology to fetal images obtained by 3DUS, MRI and CT (Armillotta et al., 2007; Willis et al., 2007; Robiony et al., 2007; Werner et al., 2010).

Additive manufacturing is the automatic, layer-by-layer construction of physical models using solid freeform fabrication. The first AM techniques were used in the late 1980s to produce models and prototypes and classified by different authors into three main categories, according to the physical state of the materials to be transformed: liquid-based systems (associated with photosensitive resins), powder- based systems (associated with sintering or agglutination of grain particles) and solid- based systems (associated with non-powder formats, such as sheets or thermoplastic extruded filaments).

There are currently several different systems of additive manufacturing technologies on the market that, although using dissimilar material procedures, are based on the same principle of manufacturing by layer deposition. One of the most important features of additive technology is the possibility of manufacturing parts with significant geometrical complexity, a process which in conventional technologies is more expensive and lengthy, affecting both the time taken to launch the product commercially and the total costs of production. Additive systems can typically produce models in a few hours, although this time varies widely depending on the type of machine being used, the size of the model to be built, the spatial positioning, the level of accuracy and the number of parts being produced simultaneously.

Nowadays, interesting trends relating to additive equipment are the so-called '3D printers', a market for which is growing rapidly. Being smaller in terms of overall size than the regular equipment, and consequently having a reduced area of construction envelope, these 3D printers also have the potential to become more 'office friendly' and also less expensive, in order to be accepted in the same way as the laser and inkjet paper printers in common use in offices.

2. Imaging scanning technologies carried out in pregnancy

Image-scanning technologies have led to vast improvements in medicine, especially in the diagnosis of fetal anomalies (Steiner et al., 1995; Campbell, 2006). In general, three main technologies are used to obtain images within the uterus during pregnancy i.e. 3DUS, MRI and CT. The development of ultrasound scanning during the 1960's opened a new window into the study of the fetus. It is currently the primary method of fetal assessment during pregnancy because it is patient friendly, useful, cost effective and considered to be safe (Campbell, 2006).

Although there is a history of more than fifty years of Ultrasonography scanning to assist the diagnostic visualization by two-dimensional methods, enhanced in the late 1980s with the advent of the 3D visualization through the use of USG 3D[1] equipment, the representation in a physical context presented in this work is a new approach, since it is focused on three-dimensional physical didactic models of fetuses from the first, second and third trimesters, created from data files obtained from Ultrasonography 3D, Magnetic Resonance Imaging and even Computed Tomography scans, together with Additive manufacturing systems.

[1] Von Ramm, O; Smith, S. *Three-dimensional imaging system* (U.S.Patent 4,694,434. Duke University, 1987)

Many centers are exploring 3D US because of the life-like images if the fetus it provides (Blaas et al., 2006; Peralta et al., 2006). MRI is a non-invasive method that has been used in obstetrics since the 1980s (Smith et al., 1983). It offers high-resolution fetal images with excellent contrast that allow visualization of internal tissues (Brugger et al., 2006; Jani et al., 2007; Daltro et al., 2008). When ultrasound yields equivocal results, MRI is generally used, because it provides additional information about fetal abnormalities and conditions in situations where ultrasound cannot provide high-quality images (Frates et al., 2004; Prayer et al., 2006). CT is used only in specific cases of suspected fetal malformation, particularly those related to the skeleton, because of potential risks associated with radiation exposure to the fetus. Its use during pregnancy must be adequately justified and its application is limited to specific pathologies such bone dysplasia, which can, in some cases, be difficult to diagnose by ultrasound especially in the absence of family history of the disease (Cassart et al., 2007; Werner et al., 2008).

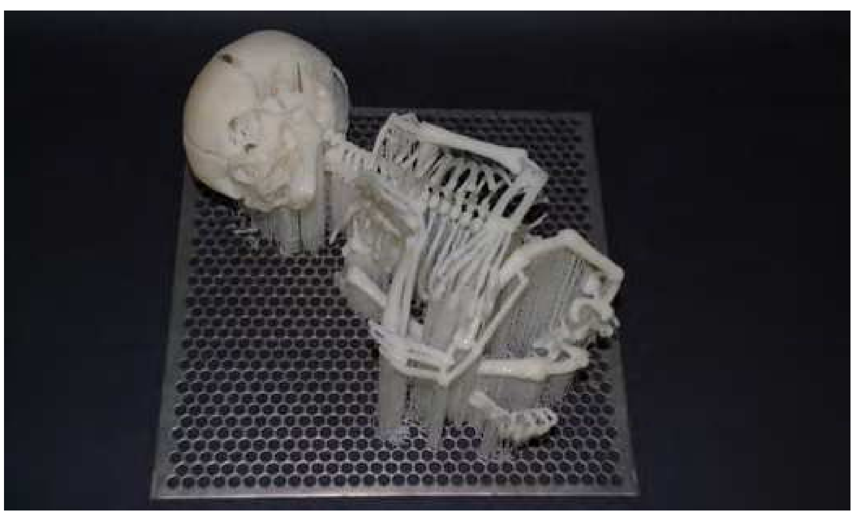

Fig. A. 34 weeks Physical model of fetus built from CT scan through SLA process (3D systems – VIPER Si).

Fig. B. 34 weeks, 3D virtual and physical models of the skeleton of the fetus built on SLA (3D systems - Viper Si) from CT scan.

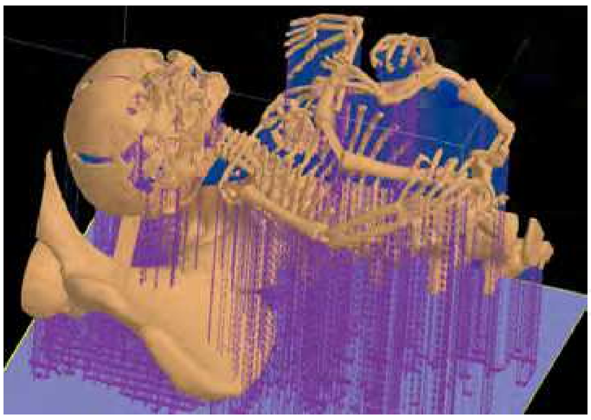

Fig. C. Virtual 3D model of skeleton including support structures for the Stereolitography process.

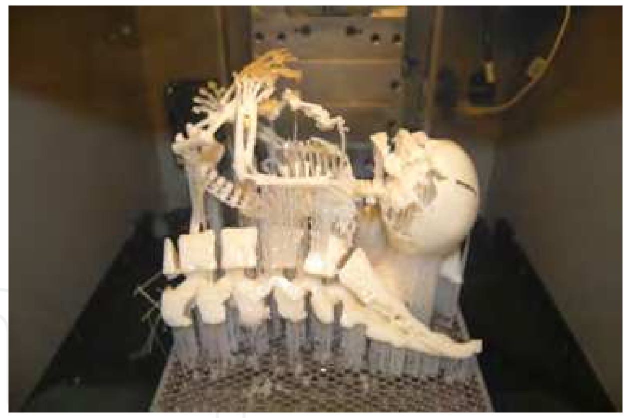

Fig. D. 34 weeks Physical model of fetus built from CT scan through SLA process (3D systems – VIPER Si).

3. Brief history of the use of didactic models in medicine

The early registered attempts to represent the fetus and the interior of the womb during the gestation, dates from around 1500, and examples of artistic drawings are spread around museums and private collections throughout the world. Among the artists who achieved a refined quality in terms of visual representation of fetuses, Leonardo Da Vinci, is undoubtedly the one who demonstrated through various detailed anatomic studies, the growing process of the fetus in the womb environment.

The use of didactic physical models in medicine began in Italy from the Renaissance onwards with the appearance of the colored wax teaching models representing different parts of the human body with visual realism, including the alterations of the woman body during the pregnancy period. The important cities regarding artistic and cultural aspects on that stage were Bologna and Florence, and the diffusion of anatomic models made of wax, created in order to teach anatomy without having to directly observe a real corpse, was emphasized through the famous "Florentine school", an art introduced in Florence by Ludovico Cigoli (1559-1613).

Among the recognized artists, Clemente Susini (1754-1814) who made the most important pieces of the collection on the laboratorial facilities of the Museum and the Sicilian sculptor Gaetano Zumbo (1656-1701), were the skilled wax modelers who contributed to the development of the medical sciences by carrying out an intensive research on the physical reproduction of anatomy by the use of wax models.

Many of these didactical models were constructed during the period between approximately 1550 and 1800 reaching its maximum period of technical and scientific splendour during the 18th century. Diverse models still can be appreciated in the permanent exhibition at the Museum of Zoology and Natural History "La Specola" in Florence, which was officially inaugurated in 1775 and until the early years of the l9th century was the only scientific museum specifically created for the public. Nowadays the Museum is unique on its collection of anatomic wax models.

Another interesting initiative happened in France, more specifically on the villages of Royaume, when around 1778, a very interesting set of hand made didactical models called

"*La machine*", made of different types of fabric, were created and produced by *Madame* Du Coudray, being its use largely adopted around different villages in order to teach and disseminate information about the birth process through the stylized models of fetuses and the mother.

The fetus as a real image of human form appeared in the pioneering work of the photographer Lennart Nilsson, who started to take pictures of dead fetuses, having his works published on the "Life magazine" in 1965. Within the years and the technological advance of fiber optics, Nilsson developed more advanced photographic techniques, being possible to see very clear bi dimensional images of live fetuses when inside the womb.

Nowadays, it is possible to find several companies that dedicate its production to the construction of didactical physical models representing all the gestation phases, from the surge of the embryo to the new born babies, including examples of the normal and healthy expectance and as well malformations occurred during the pregnancy, possible diseases and others. These models are intended to be used in medicine schools and related areas as a visual and tactile aiding information. In some cases, their appearance can have very impressive characteristics, exhibiting details such as veins, blood vessels and others. The fabrication processes of these models begin in general with the production of a prototype, hand made by a specialized modelmaker, which after the approval, will be replicated through the use of moulds.

Fig. G, H and I. Physical models built on Z Corp 510 developed from Ultrasound 3D scan files obtained in different initial pregnancy periods: twin embryos with 9 weeks in the womb, twin fetuses with 11 weeks in the womb and 13 weeks fetus in the womb.

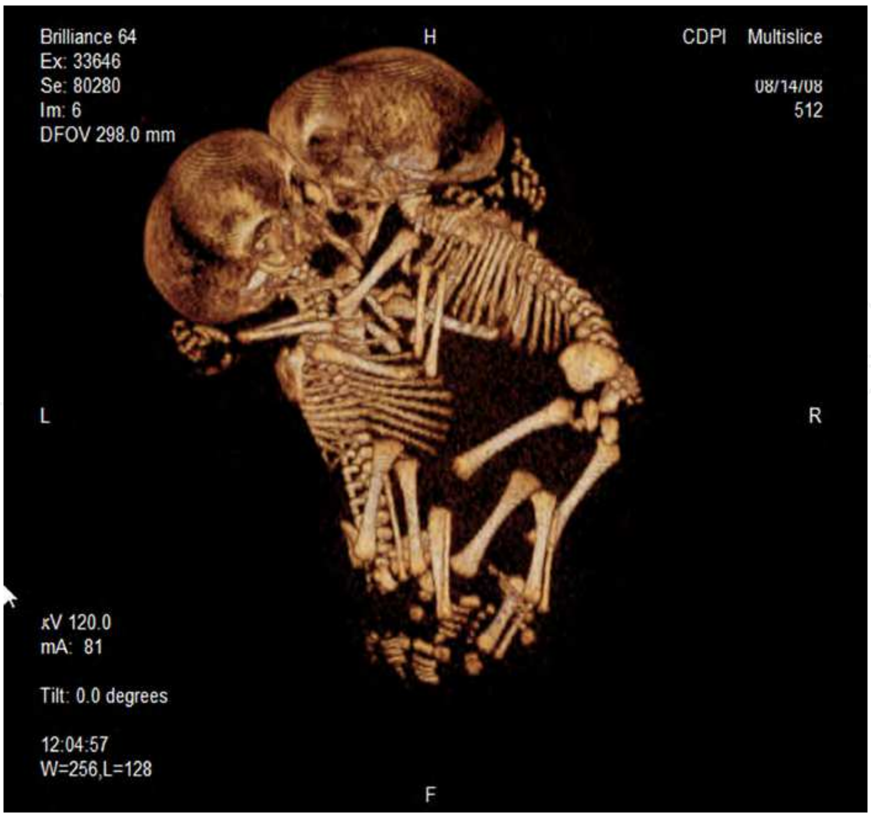

Fig. J. Virtual 3D model of 35 weeks conjoined twins generated during the CT scanning process

4. Methods and technologies applied on the project

AM was performed after 3DUS, MRI or CT of fetuses at different gestational ages. The indications for MRI were central nervous system, thoracic, gastrointestinal or genitourinary malformations, and for CT, skeletal malformations after the period of 30 weeks. The ethical issues associated with this work were carefully considered. All cases were examined first by ultrasound imaging. 3DUS scans were performed transvaginally and/or transabdominally using a high-resolution ultrasound probe with harmonic imaging for all examinations (4-8 MHz transducer, Voluson 730 Pro/Expert system, General Electric, Kretztechnik, Zipf, Austria). MRI examinations were performed using a 1.5-T scanner (Siemens, Erlangen, Germany). The protocol consisted of: T2-weighted sequence in the three planes of the fetal body (HASTE; repetition time, shortest; echo time, 140 ms; field of view, 300–200 mm; 256 × 256 matrix; slice thickness, 4 mm; acquisition time, 17 s; 40 slices) and (TRUFI; repetition time, 3.16 ms; echo time, 1.4 ms; field of view, 340 mm; slice thickness, 1,5 mm; acquisition time, 18s; 96 slices). The entire examination time did not exceed 40 min. CT was performed using a multislice 64 scanner (Philips, Solingen, Germany) with the following parameters: 40 mA, 120 kV, 64 slices per rotation, pitch 0.75 and slice thickness 0.75 mm. This corresponds to a mean radiation dose to the fetus of 3.12 mGy (CT dose index weighted). The acquisition lasted around 20 s and was performed during maternal apnea.

In order to construct physical models from the medical examinations (3DUS, MRI and/or CT), for several researches, the first step was the production of three-dimensional (3D) virtual models. All 3DUS, MRI and CT images were exported to a workstation in Digital

Imaging and Communications in Medicine (DICOM) format for segmentation done by a 3D modeling technician and supervised by the physician responsible. The 3D structure of the fetus was reconstructed by generating skinning surfaces that joined the resulting profiles. Software that converts medical images into numerical models (Mimics v. 12, Materialize, Leuven, Belgium) was used for 3D virtual model reconstruction, and the model was exported into a Standard triangular language (STL) format and converted into an "OBJ" extension for adjustment using 3D modeling polygonal software (Autodesk Mudbox, San Francisco, USA). Using this software, the volumetric surface was smoothed, to be later compared and analyzed as a topographic construction. After this procedure, the 3D model was again converted and exported as an STL extension. The model file was again opened in Mimics software for correlating the contours of the 3DUS, MR or CT images with the generated 3D surface.

The physical modeling process was done through using four different AM technologies (SLA Viper, Objet Connex 350, ZCorp 510 and FDM Vantage). Essentially, the technological processes of medical imaging acquisition and AM systems are very similar in terms of their logical procedure: the idea of acquiring images from medical scans is based on “slicing” the physical body being scanned. Through the capture of several slices (from Ultrasonography, Magnetic Resonance and Computed Tomography) the later construction of a virtual 3D CAD model can be achieved, through the superimposition of those same layers. The AM process begins with the virtual 3D CAD model which is “sliced” in layers in order to later deposit various materials, layer on layer, resulting in a physical 3D model.

Fig. O. Physical model of 34 weeks fetus built on Z Corp 510 from Magnetic Resonance scan.

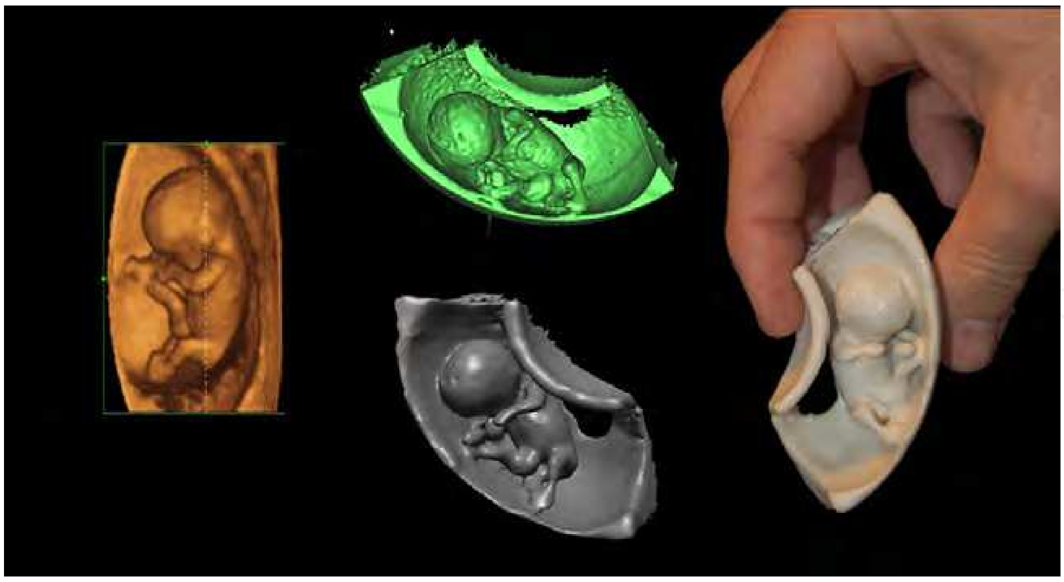

Fig. P. 11 weeks virtual and physical model of fetus built on Z Corp 510 from Ultrasonography 3D files.

Fig. L. 35 weeks conjoined twins physical models of the skeleton built in SLA (3D systems - Viper Si)

Fig. N. 32 weeks physical model of fetus built in Objet Connex 350 showing the skeleton and the structure of the uterus (transparent).

Fig. E. 32 weeks fetus built on Z Corp 510 from MRI files – on the left including the uterus and the umbilical cord and on the right only the body of the fetus.

Fig. F. 26 weeks physical model of fetus built in Z Corp 510 from Ultrasonography 3D files.

5. Results

In this study the main outcomes presented were the possibility to create 3D virtual and physical models from 3DUS, MRI or CT both separately and also in various combinations. AM systems allow the conversion of a 3D virtual model to a physical model in a fast, easy and dimensionally accurate process. The construction process transfers a 3D data file that specifies surfaces and solid internal structures to AM equipment that builds physical models through the superimposition of thin layers of raw materials. The models were remarkably similar to the postnatal appearance of the aborted fetus or newborn baby, especially in cases with pathology.

Fig. K. Slice showing the laser beam during the hardening process of the photo sensible resin on SLA VIPER Si

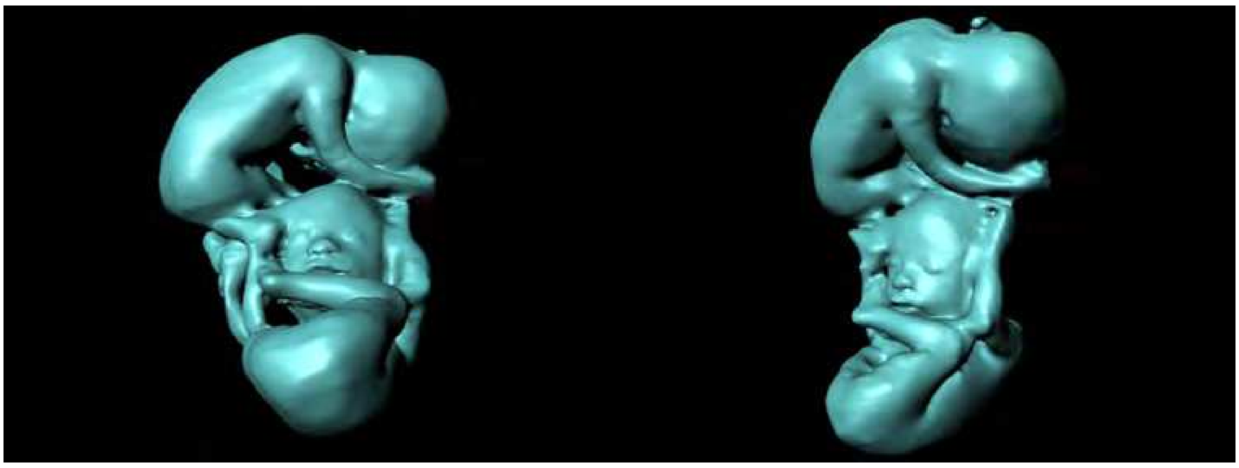

Fig. Q. Virtual 3D model of 28 weeks twins from MRI scan allied to Ultrasonography 3D.

Fig. S. Physical model of 28 weeks twins built on Z-Corp 510 from MRI scan allied to Ultrasonography 3D.

6. Conclusions

This study introduced the innovative use of AM models into fetal researches, an area where studies on digital 3D modeling have been scarce. The results suggest a new possibility for educational purposes (as medical students and blind people) or better interaction between parents and their unborn child during pregnancy, by physically recreating the interior of the womb during gestation, including physical appearance, actual size and malformations in some cases.

7. References

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