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A digital approach for design and fabrication by rapid prototyping of orthosis for developmental dysplasia of the hip

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Abstract **Introduction:** Immobilization in a hip spica cast is required in surgical and nonsurgical treatments for children aged three months to four years diagnosed with developmental dysplasia of the hip. Skin complications are associated with the use of the spica cast in 30% of the cases. This research explores the use of photogrammetry and rapid prototyping for the production of a lighter, shower friendly and hygienic hip orthosis that could replace the hip spica cast. **Methods:** Digitalized data of a plastic dool was used for design and fabrication of a customised hip orthosis following four steps: 1) Digitalization of the external anatomical structure by photogrammetry using a smartphone and open source software; 2) Idealization and 3D modeling of the hip orthosis; 3) Rapid prototyping of a low cost orthosis in polymer polylact acid; 4) Evaluation tests. **Results:** Photogrammetry provided a good 3D reconstruction of the dool's hip and legs. The manufacture method to produce the hip orthosis was accurate in fitting the hip orthosis to the contours of the doll. The orthosis could be easily placed on the doll ensuring mechanical strength to immobilize the region of the hip. **Conclusion:** A new approach and the feasibility of both techniques for hip orthosis fabrication were described. It represents an exciting advance for the development of hip orthosis that could be used in orthopedics. To test the effectiveness of this orthosis for developmental dysplasia of the hip treatment in newborns, material and mechanical tests, design optimization and physical tests with patients should be carried.

Keywords: Developmental dysplasia of the hip, Orthosis, Rapid prototyping.

Introduction

Developmental dysplasia of the hip (DDH) is a spectrum of anatomical abnormalities in the immature hip joint in which the femoral head has an abnormal relationship with the acetabulum (Storer and Skaggs, 2006). DDH occurs in newborn infants and it varies from milder acetabular dysplasia to complete dislocation of the femoral head (Yang and Quanjun, 2012) (Figure 1). DDH is usually asymptomatic during infancy - Guarniero (2010) demonstrated an incidence in Brazil of 5 per 1,000 cases. The etiology of DDH is multi factorial including ligament laxity, breech presentation, postnatal positioning and primary acetabular dysplasia (Schwend, 2014). Uncorrected DDH is associated with long-term morbidity such as gait abnormalities, chronic pain and degenerative arthritis (Noordin et al., 2010; Schwend et al., 1999).

The aim of the DDH treatment is to achieve and maintain concentric reduction of the femoral head into the acetabulum. If diagnosed during the first six months of life, DDH can be corrected with nonsurgical methods that includes the use of orthotic devices for hip repositioning and to keep the femoral head in the correct position in the acetabulum. Pavlik harness, a brace straps and fasteners, is used to fit around a child's chest, shoulders and legs being the standard treatment for DDH. This is a dynamic positioning device that avoids complete immobilization of the joint, prevents hip extension and adduction but allows flexion and abduction (Storer and Skaggs, 2006; Wahlen and Zambelli, 2015). If a dislocated hip is not reduced within three weeks, the Pavlik harness should be discontinued and an alternative treatment selected. The next option involves closed reduction under anesthesia with the use of a hip spica casting, a plaster cast used to keep the affected hip joint of the newborn in the best position for normal growth (Rampal et al., 2008; Storer and Skaggs, 2006; Vitale and Skaggs, 2001). The position of the femoral head in a spica cast of a child with DDH needs to be confirmed accurately and monitored routinely by imaging methods (Teng et al., 2012). The shape of the hip spica cast varies and can be extend from the mid-chest down to the ankle; sometimes a bar between the legs strengthens the cast. An opening in the genital area allows normal urine and bowel elimination. Hip spica casts are usually worn for two up to three months and cannot be removed before this period of time (Steps, 2010).

Caring for a child in a hip spica cast is extremely challenging. The spica must be kept dry, if water is

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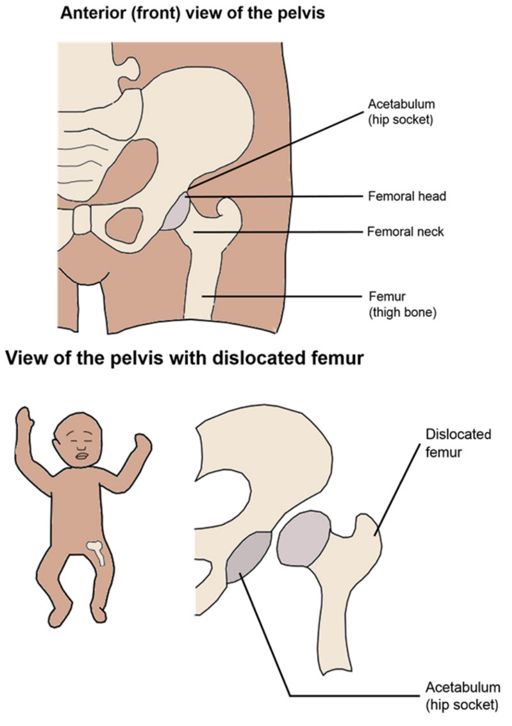

Figure 1. Handmade drawing of the pelvis and description of the developmental dysplasia of the hip (DDH).

absorbed into the spica the plaster will become weak and may crack. Daily tasks such as changing nappies and bathing of a child in a hip spica takes extra time and practice. It is not possible to bath a child using a hip spica and thorough wash with a damp cloth at least once a day is required. The lack of bathing and the pressure of the cast on the spine cause skin complications in 30% of the cases (Difazio et al., 2011; Halanski and Noonan, 2008). In general, children in casts only sleep for short periods and often become restless and distressed. Disturbed nights can be caused due to the occurrence of cramp, itching and the inability to turn over. It is necessary to change the child's position every 2-4 hours (The Royal…, 2015; Steps, 2010).

Surgical methods are an option of treatment for children in whom nonoperative treatment with hip spica has failed or in children diagnosed after six months of age. The treatment includes open reduction of the hip with femoral or acetabular osteotomy also followed by the use of hip spica cast (Mulpuri et al., 2015). Families, especially mothers, experience problems providing home care after their child's surgery, the most frequently related problems are hygiene/care after toileting, cast and skin care, and personal hygiene (Demir et al., 2015).

The literature has reported the use of some orthotic devices in treatment of the DDH, such as rigid and semirigid abduction braces, to replace the use of Pavlik harness and the spica cast (Dyskin and Ferrick, 2015; Hedequist et al., 2003; Ibrahim et al., 2013; Uras et al., 2014; Wahlen and Zambelli, 2015; Wilkinson et al., 2002). The use of an abduction brace is easier for the patient, parents and the physician. However, current literature provides controversial results of treatment of DDH with these plastic abduction orthoses and since the results depends on severity of hip dysplasia more research is needed.

Because every patient with DDH has an unique anatomy (Yang and Quanjun, 2012), custom made orthoses remain the 'gold standard' once the orthotic geometry is tailored to each patient. Improved clinical effectiveness has been linked to customised orthesis over massproduced ones (Brncick, 2000). However, the manual fabrication of a custom-fit orthosis is a laborious, time-consuming and imprecise process performed by skilled orthotists in order to create comfortable and functional devices. Due to the reduced cost, in some contexts there has been an increasing preference for prefabricated orthoses (Majumdar et al., 2012). There is a great need for customised products in the field of orthotics since not all patients can be treated with standard sized orthesis.

In recent years, some attempts to use new technologies in the manufacture of patient specific orthotics have shown good results. Computerized techniques for manufacture of patient-specific orthotic devices have the potential to provide excellent comfort. Otherwise it allows changes in the standard design to meet the specific needs of each patient (Mavroidis et al., 2011). The main phases of this process includes: a) 3D Scanning of an anatomical structure and 3D digital model reconstruction, b) Orthosis design and c) Production of the orthosis by a manufacture process.

Laser scanners, structured light scanners, scanners with video cameras and photogrammetry are the main technologies that could be used for 3D anatomic surface scanning. A laser scanner device uses a laser beam normal to the surface to be scanned. There are several commercial devices that are relatively easy to use. The aplication of laser scanner in the production of medical devices can reach 98% of accuracy (Igathinathane et al., 2010), but the equipment cost is still relatively high (Milusheva et al., 2006). Photogrammetry technique allows obtaining spatial measurements, and other geometrically reliable information, derived from photographs captured from different points of view. This portable and low-cost technology uses automated matching algorithms to produce a dense point cloud of an object and its 3D reconstruction through a post-processing procedure (Remondino, 2003). Ciobanu and Rotariu (2014) reported that photogrammetry has been used in the orthopedics field e.g. treatment of scoliosis (Aroeira et al., 2011), deformational plagiocephaly (Moghaddam et al., 2014) and prostheses/ortheses fabrication (Ciobanu et al., 2013a; 2013b).

Additive manufacturing (AM) describes a set of new manufacturing methods, processes and technologies that function through material addition, in contrast to the established traditional cutting, forming or casting models. Rapid prototyping (RP) technologies are the most widely applied and known fabrication methods based on AM principles. The fused deposition modeling (FDM) is a process to produce 3D solid components from digital models using additive techniques and creating by laying successive layers of material. The continuous improvement of RP system accuracy and materials expand gradually the applications to other areas (Giannatsis and Dedoussis, 2009). AM and RP technologies have been used for product development and design process due to their relatively high speed and flexibility. These technologies have also been employed in various non-manufacturing applications such as medicine and health care (fabrication of custom made implants and scaffolds for rehabilitation, models for pre-operating surgical planning, and anatomical models for mechanical testing) (Giannatsis and Dedoussis, 2009). While the application of RP in developing countries is still at early stage, some recent studies have investigated feasibility of using AM and RP in the manufacture of orthoses. Palousek et al. (2014), Patar et al. (2012), Paterson (2013) and Paterson et al. (2010; 2014a; 2014b; 2015) have developed new methods to support the mass customization of wrist splints. Jumani et al. (2014) used FDM for fabrication of custom-made foot orthoses, and Mavroidis et al. (2011) used RP to produce an ankle-foot orthose. For the authors' knowledge, no data are available in the literature about new approaches for design and production of orthoses for children's hip by photogrammetry and RP.

The difficulties encountered in day-to-day care of children using hip spica cast during treatment of DDH have been the motivation of the current study (Steps, 2010). There is a growing interest in new techniques of production of abduction brace orthoses in attempt to avoid these complications (Dyskin and Ferrick, 2015; Munhoz et al., 2014; 2015). A hip orthosis produced using RP method could provide a highly technical support system that can be fully ventilated, light, shower friendly, hygienic and stylish. In this study, a new approach was developed to combine photogrammetry with RP to produce a custom made hip orthosis for DDH.

Methods

In this first approach, a plastic doll was used to represent a newborn with approximately four months of age. The same procedure into a real child will require some adjustments that have not yet been addressed in this study. The methodology adopted comprised five stages.

Stage 1: acquisition of the external anatomical structure by photogrammetry

The dool's hip and legs were marked with traces randomly using a permanent black marker. The doll was placed on a stand, for elevation of the hip region, in supine position with her legs up (Figure 2). This stand was placed above a non-reflective board used as external reference with traces forming square 5 × 5 cm. The camera of a smartphone Sony Xperia R800 (Sony, 2015) with resolution of 5.1 Megapixels, 2592 × 1944 pixel, VGA, autofocus, LED flash, video 720p, CMOS sensor (Complementary Metal Oxide Semiconductor) technology without anti-vibration option was used for the acquisition of the photos. A set of 55 photos of the region of the dool's hip and legs were taken indoors with artificial light and without use of flash or zoom resources. Camera calibration was not necessary for this procedure. The photos were taken moving the camera around the doll in a spiral trajectory, in order to obtain at least two scenes that show the same point. The first sequence of photos started with the camera positioned approximately 50 cm above the doll, and with 45 degrees of inclination with the horizontal plane. The second sequence of photos

Figure 2. Experimental setup used in the photogrammetric procedure for 3D surface reconstruction of the hip and legs of a plastic doll. The doll with hip and legs marked by random traces was placed on a stand in supine position above a non-reflective plate with reference traces.

were taken by moving the camera each 15 degrees approximately in a spiral trajectory until it reaches the horizontal position (Figure 3). A computer Intel i7 (3.4 Ghz processor and 16 GB-RAM and Windows 8.1 operation system) and two free and open source softwares, Python Photogrammetry Toolbox (PPT-GUI) and MeshLab were used as described bellow: First, the 55 photos were processed using the PPT-GUI user interface. This step is required to provide the photos pathway where the JPG files is stored using the Check Camera Database tab (JPG stands for Joint Photographic Experts Group is a commonly used method of lossy compression for images produced by digital photography). The file was saved with a simple name without symbols or spaces as required to the pathway. The PPT-GUI read the JPG files looking for the camera information to recognize the sensor size, in this case, 3.8 mm width. A point cloud is a set of data points in the 3D coordinate system defined by X, Y, and Z coordinates representing the external surface of an object that was photographed. The Bundler is an algorithm of the PPT-GUI that produces point clouds from a list of unordered images. After run the Bundler a sparse point cloud was calculated requiring the photos pathway and the scale photos factor inputs that define the scale at which the 3D reconstruction should be performed. The use of a scale 1:1 generates a model in full size according to the size of the camera sensor. However this option requires larger use of memory capability and computer processing. The sparse point cloud of the doll was stored in a temporary folder and a Patch-based Multi-view Stereo (PMVS) algorithm without Clustering Views for Multi-view Stereo (CMVS) was used (Furukawa and Ponce, 2009). This last step provided a dense point cloud in a polygon file format (PLY) stored into a PMVS folder inside of the temporary folder created earlier. A PLY file supports a relatively simple description of a single object as a list of nominally flat polygons. The PLY point cloud file was imported into Meshlab software and some unnecessary points were removed. The point cloud was resized to a real measure and an useful mesh of the 3D hip and legs model of the doll was create. Using a metric tool into the software Meshlab it was possible to measure the trace dimension 5 × 5 cm in the board used as external reference plate and perform the model resizing by a scale factor. The scale factor is the ratio between the real and the current measure on Meshlab metric system. The scale factor was added into a transform scale inside the filters and normal curves and orientation (the number 1 is equal to 1 mm). After that, the reference plate was discarded and the point cloud of the dool's hip and legs was converted into a 3D mesh using a Poisson reconstruction approach (Figure 4a).

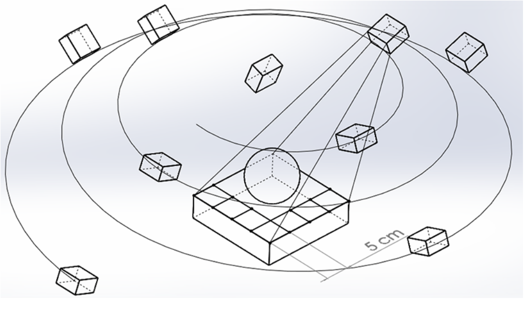

Figure 3. Photogrammetry scheme used: The sphere represents the target object, in this case the doll, over the reference plate. The cubes represent the camera of a smartphone moving in a spiral trajectory around the doll.

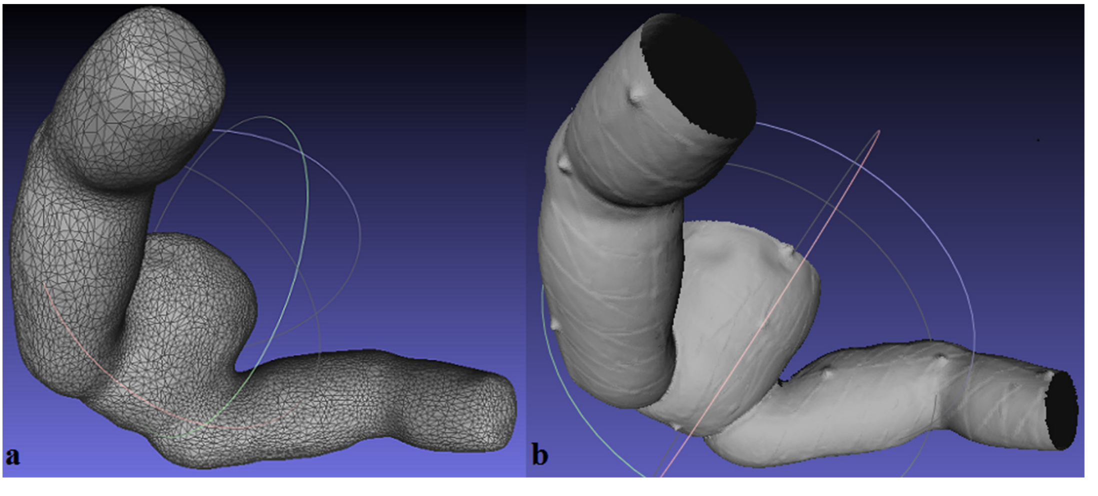

Figure 4. Meshes generated from 3D surface reconstruction of the hip and legs of the doll. a) Mesh by photogrammetry with 9,002 vertices and 18,000 faces and b) Mesh by laser scanning with 268,139 vertices and 524,044 faces.

Stage 2: idealization and modeling of a hip orthosis for DDH

Based on the 3D reconstruction of the dool's hip and legs by photogrammetry, a Computer Aided Design (CAD) based orthesis model was designed with the Blender software. The hip orthesis was designed in two separated parts (anterior and posterior) with an opening in the genital area for physiological needs and cleaning. For each part, first the left side of the orthosis was modeled then to save time and computer memory this side was mirrored in the sagittal plane. The two parts of the CAD model were then converted into a stereolithography (STL) file format using a mesh to solid converter tool. A STL format contains triangular facet representation of surfaces and have become standard data inputs of RP and manufacturing systems.

Stage 3: manufacture of the hip orthosis by RP

The free software MatterControl was used to generate a G-code of the STL file for 3D printing. G-code is used in computer-aided manufacturing to control the 3D machine tools. The MatterControl takes the CAD model, slices it into layers, and output the G-code required for each layer. Both parts, anterior and posterior, of the hip orthosis were produced in a 3DCloner machine with FDM technology (Microbras, Santa Terezinha de Itaipu, Brazil). This is a low cost and affordable 3D printer available on market for the price of 1,200 dollars. The 3D printing volume of the 3DCloner is 320 mm (width), 210 mm (depth) and 160 mm (height). The biodegradable polymer polylactic acid (PLA) in the form of a spool of 1.75 mm diameter filament was used. To produce an orthosis, 400 grams of PLA including extra pillars of polymer to support hanging structures was used. The printer configuration used 0.3 mm layer thickness and 30% fill density in the actual scale of 1:1. The hip orthosis was built from the bottom up - one layer at a time. The build time to produce the orthosis was about 30 hours.

Stage 4: evaluation - photogrammetry x 3D laser scanning

To evaluate the efficiency of the photogrammetry to 3D reconstruction of the dool's hip and legs, the volume and shape of the 3D model obtained was compared with a 3D model of the same doll obtained with a comercial Artec MHT^{TM} scanner (Artec Group Inc, Luxemburgo). This scanner has a video camera technology and projects structured light using a triangle between the scanner lens, laser, and an object being scanned. The frames are combined automatically in the scanner software into a single 3D mesh, in the 3D reconstruction phase (Ciobanu et al., 2013b). In this case, a mesh was generated in an automatic sequence with no need of additional steps as performed by the photogrammetry (Figure 4b). To compare both meshes, the open software CloudCompare was used. This is a 3D point cloud processing software to handle triangular meshes and calibrated images. The meshes were partially aligned and a topology mapping with the difference found between the two meshes was created.

Stage 5: evaluation - digital model x physical model

After production of the hip orthosis by RP its physical dimensions were compared with the 3D model reconstructed by photogrammetry. The result of this evaluation is used as an indicator of the good fit of the orthesis in doll's body and the accuracy of the PR to produce a hip orthosis. A custom orthosis that fits well the user's body shapes allows more comfort. In both CAD model of the orthosis and in the 3D printed orthosis, 16 reference points were defined for the anterior (a', b', c', d', e', f', g', h', i', j', k', l', m', n', o' and p') and 16 reference points for the posterior part (a, b, c, d, e, f, g, h, i, j, k, l, m, n, o and p) (Figure 5c). Based on these points, 16 linear parameters were defined for the anterior (a-b, b-c, c-d, d-e, e-f, f-g, g-h, a-i, i-j, j-k, k-l, l-m, m-n, n-o, o-p and p-h) and 16 parameters for thee posterior part (a'-b', b'-c', c'-d', d'-e', e'-f', f'-g', g'-h', a'-i', i'-j', j'-k', k'-l', l'-m', m'-n', n'-o', o'-p', p'-h'). The measurements of the 32 parameters in both CAD model of the orthosis and the 3D printed orthosis were performed by a single observer. In the CAD model other measurements of the linear parameters were performed using milimeters in the software Blender. In the physical model, the measurements were performed in milimeters with a Mitutoyo digital caliper (Mitutoyo Corp, Kanogawa, Japan). The difference between the linear dimensions of the digital and Physical orthosis was computed. Each set of measurements was carried out by the same observer three times. Intraobserver reliability was examined by repeating the measurement of all parameters in both digital and physical orthosis.

Results

The time required to obtain 55 photos for photogrammetry was approximately 10 minutes. The 3D surface reconstruction of the dool's hip and legs resulted in a mesh by photogrammetry with

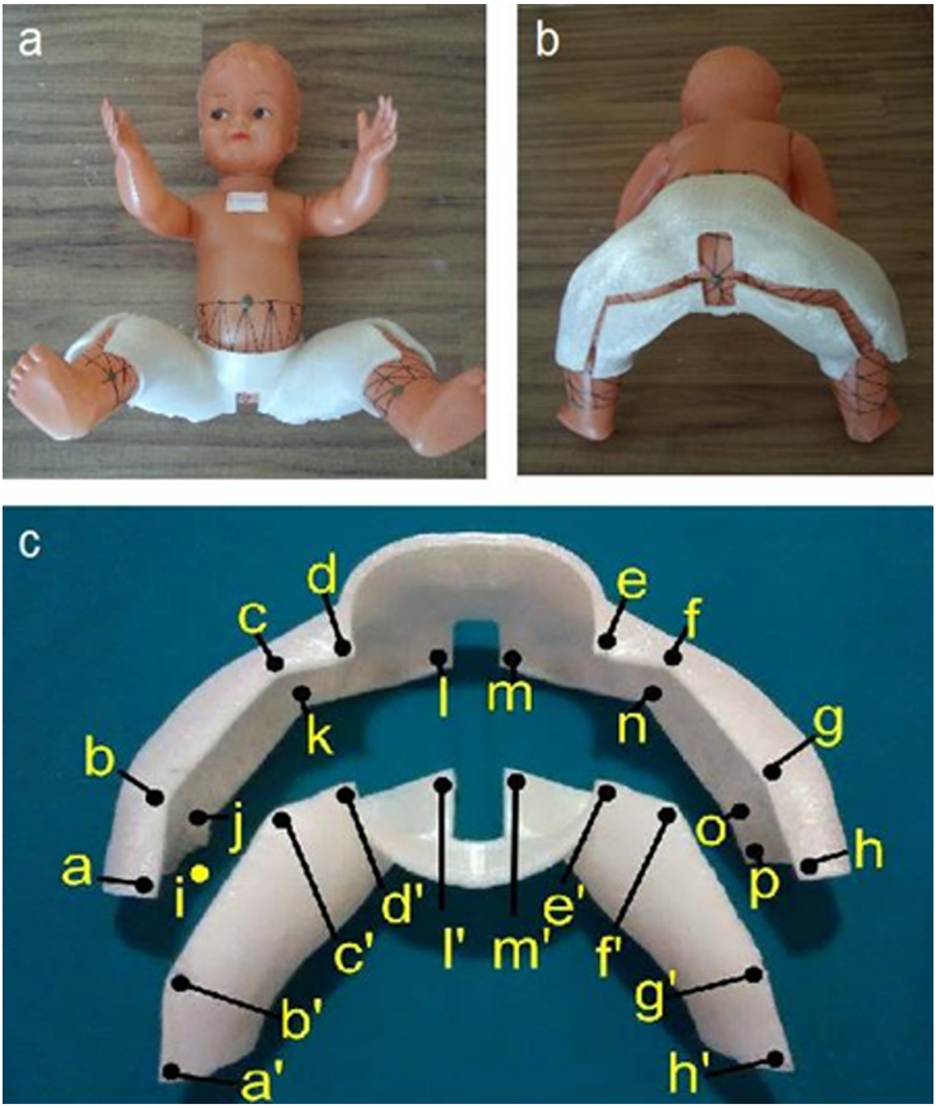

Figure 5. Children's hip orthosis produced in biodegradable polymer polylactic acid (PLA) by rapid prototyping using fused deposition modeling: a) Front and b) Down view - The manufacturing process is available in Biomecanica e Forense UNIFESP (2015); c) Schematic representation of 32 reference points (black circles) used for comparison between the digital and physical dimensions of the orthosis.

9,002 vertices and 18,000 faces (Figure 4a) and a mesh by 3D laser scanner with 268,139 vertices and 524,044 faces (Figure 4b). The number of vertices and faces using both techniques can vary due to the selected limits of the legs and waist. The number of vertices and faces also show that the resolution of the 3D model generated by photogrammetry was lower than the resolution of the 3D model generated by the laser scanner. This fact is not a problem because the fit of the prosthesis does not require high precision. Instead the low resolution requires less computer time and it is desirable that the post-processing is faster. Regardless of the number of vertices and faces, the comparison between the both meshes performed by CloudCompare software presented a difference of 10 mm (Figure 6). This implies that considering the topology of the whole model, the largest difference between a peak and a valley was found to be 10 mm and that the average difference for the whole model was 4 mm. This amplitude is presented in a topographic mapping composed of peaks and valleys superposing the difference between the two meshes, where the transition from green to red represents an elevation and the transition from a green to a blue region represents a depression. The Figure 7 shows both parts of the hip orthosis model in three diferent views (anterior, superior and posterior). The manufacturing process of the orthesis by RP is avaliable online (Biomecanica

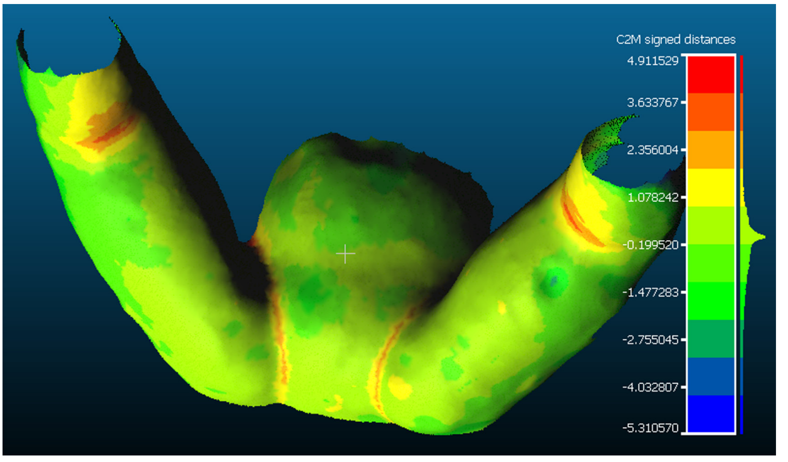

Figure 6. Topographic map generated with the CloudCompare software after comparison between the meshes from photogrammetry and laser scanning. The map is composed of peaks and valleys superposing the difference between the meshes. The transition from green to red represents an elevation and from a green to a blue region represent a depression. For the whole model, the largest difference was found to be 10 mm and the average difference was 4 mm.

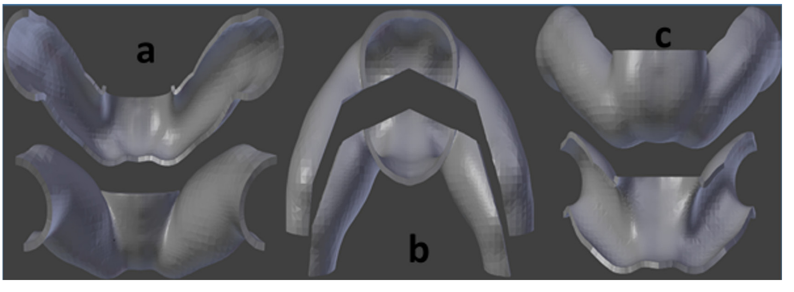

Figure 7. Three views of the digital model of the hip orthosis modeled with Blender software: a) front, b) upper and c) back. The hip orthosis was designed in two separated parts (anterior and posterior).

e Forense UNIFESP, 2015). Figures 5a, b show anterior and posterior view of the doll using the hip orthosis produced by RP. The manufacture method to produce the orthosis was accurate in fitting to the contours of the doll's hip and legs. The comparison of the linear parameters of the digital and physical model of the orthosis has shown that a low difference was found between the parameters, the greatest difference value was 5 mm (Figure 5c). It means that the contours of the dool's hip and legs were acquired with a good accuracy through the photogrammetry. The intraobserver reliability test (to compare indirect and direct measurements of the linear parameters defined in the digital and physical model) showed that measurements of the linear parameters were better repeated when obtained directly from the digital model.

Discussion

This work presented a digital approach for design and fabrication by RP of an orthosis that can be considered as an alternative for treatment of DDH. The anatomical structure of dool's hip and legs was digitalized in surface data, used as input for modeling of an orthosis in a CAD software, and later production in a RP machine.

Treatment of DDH in children from first month of age up to four years presents many challenges (Vitale and Skaggs, 2001). The overall medical cost of hip spica casting, including supplies and overall hospitalization time is low, the patients return home quickly, but the physical and financial burden of care is transfered to the family (Ferreira and Thomson, 2012). In this study, we started from the principle that a hip orthosis produced from a polymeric material by RP could replace the hip spica cast currently used for DDH treatment with the advantage of reducing some problems related to the use of this devices. In the most cases of DDH a hip spica cast is used for months in children undergoing nonsurgical and surgical treatment (Dezateux et al., 2003). Although plaster casts and splints remain an important treatment method for acute and chronic orthopaedic conditions, there are known risks associated with cast application, immobilization, and removal (Halanski and Noonan, 2008). For instance, casting materials create an exothermic reaction and skin's burns that are associated with water temperatures above 24 °C, more than eight layers and inadequate ventilation. The plaster has been the definitive management for immobilization of the skeleton for over 100 years and now there is a trend that it will be replaced by modern techniques (Daines et al., 2014; DeMaio et al., 2012). A hip orthesis produced by RP can be fully ventilated, light, shower friendly, hygienic and stylish. Such orthesis could be used not only to DDH treatment but also to treat fractures and other musculoskeletal conditions for children when rest, immobilization, or correction of deformity is required (DeMaio et al., 2012). The material used to produce the orthosis, PLA, is a polymer made from renewable agricultural raw materials, biodegradable through composting, with good stiffness and strength. Unlike plaster, a hip orthosis produced in PLA will not absorb fluids (pus, blood, or sweat). Besides such orthosis could be washed in water, it is lightweight, and could allow the skin to ventilate reducing the risk of skin lesion. As the orthosis would be placed by fitting the newborn, this procedure can prevent the need for newborn being anesthetized for each application procedure and removal of cast. However, PLA has low resistance to temperature changes (from 60°C) being necessary to avoid direct exposure of the orthosis made of this material to sunlight or hot environments for a long time.

There is no standard method for collecting topographical surface data for hip and leg of newborns and it is important that new methods can be used and evaluated. A suitable anatomical data acquisition method for anatomical structures should consider accuracy, resolution, patient comfort and safety. The current work showed the production viability of a customized hip orthosis using cost effective scanning by photogrammetry, modeling using open software and production with a low cost RP machine. The photogrammetry, is cost-effective (about ten times cheaper than the laser scaner), has the advantage of being performed with open software using a digital photo camera, even a smartphone, for digitalization of an anatomical structure. In this study, many traces were done on the doll to facilitate the identification. In a real child it would be possible to use a smaller number of traces that can be done with a non-allergic pen easily removable with water. For acquisition of the photos it is necessary that the child does not change position during the process. In a real case the child could be immobilized by their parents or in more difficult cases the child could be sedated. This is better than the usual procedure of anesthesia that occurs in the application of spica cast. Despite photogrammetry having the disadvantage of requiring considerable time during the 3D reconstruction phase, new free software such as Autodesk 123D Catch faster and easier to use were released after the realization of this study. The laser scanner has the main advantage of fast processing for 3D reconstructions but is more expensive than photogrammetry (Ciobanu et al., 2013b). Both techniques allow the production of hip orthosis with less direct contact with the patient causing less stress with good repeatability (Palousek et al., 2014). Our results showed that both photogrammetry and 3D laser scanners provided adequate quality for 3D reconstruction of dool's hip and legs with suitable accuracy and resolution (Figure 4a, b). The difference of 10 mm found between the two 3D reconstructions is not relevant when compared to the size of the dool's hip and legs. However, in both cases post processing is required to create a digital model suitable for RP (Paterson et al., 2010). Similarly, the 5 mm of difference found between the digital model and the physical orthosis (Figure 5c) do not imply a bad adjustment of the orthosis in doll hip. The rapidly prototyped orthosis showed a good fit on the plastic doll used as subject (Figure 5a, b). Generally, the production of orthoses as braces or a hip spica cast require the presence of well-trained occupational therapists or expert, which can not be found in every clinic set-up. The approach using RP do produce a hip orthosis for DDH tratment has potential for decreasing fabrication time and cost, especially when a replacement of the plaster cast is required.

In this study, it was chosen the option of using a biodegradable polymer material, PLA, for the production of a lightweight and water-resistant hip orthosis. PLA is a well-known material with suitable mechanical properties and thermoplastic processing capabilities and it is one of the most suitable polymers for medical applications. Generally, polymers have been used in medical applications such as suture production, drug delivery and scaffolds for repairing damaged tissues (Yazdanpanah et al., 2014). The cost estimation to produce the orthosis in this study, considering only the PLA was about 16 dollars. A comparison with cost of other hip devices (Pavlik harness 434 dollars, brace 650 dollars and hip spica cast 400 dollars) should also include hospital expenses as anesthesiologist and operating room (Santili et al., 2005; Wahlen and Zambelli, 2015). The main advantage of the presented approach can be summarized as follows (Table 1): 1) Easy to store and transfer of data: All the details of the hip and leg surface could be stored in image format and the hip model could be reconstructed from the photos and stored in STL format. The approach is a easy way to help people from the remote parts of a country to be able to access medical care; 2) Simple design technique: To design and produce the hip orthosis only a smartphone with camera and a 3D printer is required; 3) Comfort and stability for the user: This orthosis is customized to

Table 1. Comparative summary of the main features of the techniques explored in this study (acquisition of images for 3D reconstruction and manufacturing of orthotic devices for hip). The summary also includes a qualitative comparison between the use of a hip spica cast and a hip orthosis produced by rapid prototyping in developmental dysplasia of the hip treatment (a quantitative comparison requires further study with volunteers).

Image acquisition process for 3D reconstruction			Manufacturing process for orthotic device for hip			Device for developmental dysplasia of the hip treatment		
Features	**Photogrammetry**	**3D Laser scanning**	**Features**	**Traditional process of spica casting**	**New process by rapid prototyping**	**Features**	**Hip spica cast**	**3D printed hip orthosis in polylactic acid**
Hardware cost	Low	Very high	Cost	Low	Medium	Cost	Low	Low
Portability	High	High	Contact with the patient	Yes	No	Malleability	Excellent	Excellent
Mobility	High	High	Surgical center	Yes	No	Risk of skin complications	High	Low
Exposure time	Low	Very low	Exposure time	High	Low	Risk of allergic reaction	Low	Low
Post processing	Medium	Little	Request anesthesia	Yes	No	Diaper exchange task	Highly impaired	Easy
Need for markers	Yes	No	Request an expert	Yes	No	Task sanitize	Highly impaired	Easy
Hardware Weight	Low	Very low	Healing process	High	-	Water resistance	Low	High
Safety	High	High	Safety	Medium	High	Mechanical resistance	Medium	Medium
Computer requirements	Medium	Medium	Stress for the patient	High	Medium	Temperature resistance	High	Low
Resolution	Medium	High	Reproducibility	No	Yes	Possibility to remove	No	Yes
Accuracy	High	Medium	It can be done remotely	No	Yes	Weight	High	Very low
Usability	Hight	Medium	Request 3D reconstruction of the patient	No	Yes	Aesthetics	Low	High

an individual child's hip and all bony prominences and the anatomical contours of the hip and legs are takes into account. This procedure will give more stability to the part of the patient's body where the orthosis is fixed. Improving the comfort of the child reflected in reduce the difficulties already reported by parents to perform day to day tasks associated with taking care for a child with DDH.

A new manufacturing methodology for a hip orthosis that could replace the use of hip spica cast was described. The fabrication of hip orthosis using photogrammetry and RP is fully feasible. These techniques represent an exciting advance for the development of hip orthosis that could greatly facilitate orthopedic research. In a future approach, material and mechanical tests, design optimization and physical tests with patients should be carried to test the effectiveness of this new orthosis for DDH treatment in newborns.

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