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An Update on Orthopedic Applications Using 3-Dimensional Printing Technologies

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***Abstract*—**This article reviews the technological applications of 3-dimensional printing (3DP) in orthopedics. 3DP is the manufacturing process to build three-dimensional object by accumulating material, and recently it is drawing the interest of medical professional significantly. Orthopedics is probably the biggest application of this technology, and is being tested from surgical planning to the implant manufacturing to prove its usefulness. The technology has not overcome the problems that arose in the 90s completely, those limitations will be overcome eventually, when the technological development speed is considered.

***Keywords*—**3D Printing, Orthosis, Orthopedics, Surgical Planning, Prosthesis.

UNA ACTUALIZACIÓN SOBRE APLICACIONES ORTOPÉDICAS USANDO TECNOLOGÍAS DE IMPRESIÓN TRIDIMENSIONAL

***Resumen*—**En este artículo se revisan las aplicaciones tecnológicas de la impresión tridimensional (3DP) en Ortopedia. La impresión 3D es el proceso de manufacturar para construir objetos tridimensionales a través de la acumulación de material, y recientemente está llamando la atención de profesionales médicos de forma significativa. La Ortopedia es probablemente la mayor área de aplicación de esta tecnología, y está siendo probada en diversos procedimientos, desde hacer planeación quirúrgica hasta manufacturar implantes para probar su utilidad. Sin embargo, esta tecnología no ha superado completamente los problemas que surgieron en la década de los noventa, estas limitaciones serán superadas eventualmente cuando la velocidad del desarrollo tecnológico sea considerada.

***Palabras clave*—**Impresión 3D, Órtesis, Ortopedia, Planeación Quirúrgica, Prótesis.

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UMA ATUALIZAÇÃO EM APLICAÇÕES ORTOPÉDICAS USANDO TECNOLOGIAS DE IMPRESSÃO TRIDIMENSIONAIS

***Resumo*—**Este artigo descreve as aplicações tecnológicas da impressão tridimensional (3DP) em Ortopedia. Impressão 3D é o processo de manufatura para construir objectos tridimensionais, através da acumulação de material. Recentemente elas estao atraindo significativamente a atenção dos profissionais médicos. A Ortopedia é provavelmente a maior área de aplicação desta tecnologia, e está sendo testado em vários processos, desde o planejamento cirúrgico até a fabricação de implantes cirúrgicos para provar a sua utilidade. No entanto, esta tecnologia não foi consigue superar completamente os problemas que surgiram na década dos noventa. Essas limitações serao superadas quando a velocidade do desenvolvimento tecnológico seja considerado.

***Palavras-chave*—*I*mpressão 3D, *Ó*rtese, Ortopedia, Planejamento Cirúrgico, Prótese.**

I. INTRODUCTION

Three-dimensional printing (3DP) is the process to manufacture three-dimensional object by accumulating material. Many researchers noticed the possibilities of the technology, as soon as it was suggested originally by Kodama [1] of Japan in 1981. Hence, for example, Chuck Hull patented his original idea, which is called stereolithography [2] in 1984 and started own business using the technology. On the other hand, it is not long before 3DP really drew the interest of medical professionals due to the availability of the technology. Recently the technology is rapidly being introduced to orthopedics.

Why are 3DP technologies so adequate for orthopedics? Probably, the first reason is all human bodies are different, and therefore basically requires customized service. The second reason is many human organs are so complex structure to replicate using the conventional technology.

Interestingly, there exists researchers who noticed early the applicability of 3DP for orthopedic purpose, for example, [3, 4], published in earlier 1990s, describe the prosthetic socket using a 3DP technology. However, the technology could not be easily justified since it was not mature enough at the time; one report of 1998 analyzed that the cost is too high, the manufacturing time takes too long, and material property is very limited when compared with the traditional methodology even if possible [5].

The expiration of the core patents made 3DP more popular, and now affordable 3D printers can be purchased in online stores such as Amazon with less than 300 dollars. Now hundreds of patents expired and those technologies are available without cost. Every year the 3DP machine manufacturers announce board range of materials to print and much faster printing time. For example, one product announced by Hewlett Packard in 2016 is claimed to be 50% cheaper and ten times faster [6].

Indeed, all addressed problems of 3DP for orthopedic applications are disappearing gradually, and a significant amount of clinical evaluation of the technology are being reported every day. In this review, we try to summarize the recent progress of orthopedic applications of 3DP technologies in a few selected areas and try to discuss the near future of the technology.

II. SURGICAL PLANNING

3DP technologies have shown a great potential in surgical planning as they may provide models of human structures matching the individual characteristics of each patient, providing better understanding of anomalies. Furthermore, limitations of medical images which can only be seen in screens can be overcome by using 3DP models [7]. Based on volumetric medical images containing three axis information such as computed tomography (CT) or magnetic resonance imaging (MRI), the organs or structures of interest can be segmented and post-processed to be 3D printed [7].

Various researchers used this tool to perform complicated surgical procedures in different parts of the body. Jacobs (2008) used 3DP technology to create an anatomical model of cardiac structures to plan and execute the resection of an aneurysm and a tumor inside the heart, and it improved the surgical planning and orientation [8]. Another example of a particular successful case is the one reported by Tam (2012), in which a 3DP model of the scapula of a 6 year old girl with a large scapular osteochondroma was used to plan the surgery, as it allowed the surgeon to improve the anatomical understanding of the lesion [9]. Karlin (2016) reported that 3DP spine models improve the outcome of the surgery to correct myelomeningocele deformity [10].

Additionally, preoperative planning in living donor liver transplantation has been improved by using a 3DP liver model. Zein (2013) reports that this method safeguards both donor and recipient as it is not only useful during preoperative surgical planning but also permits to identify vascular and biliary tract anatomy which can be used to prevent unnecessary surgery in patients with unsuitable anatomy, decreasing the complications of the surgery [11].

The accuracy of the technology in surgical planning was studied by Van Assche (2007) by imaging formalin-fixed cadaver jaws through CT and 3DP the same structure based on these images. Data allowed an accurate implant and surgery planning. Evaluation was done by imaging the 3DP jaw implant through CT and evaluating the deviation, and showed that CT images could be used for implant planning considering a certain angular and linear deviation [12].

A particular case is the one reported by Schmauss, in which a 70-year-old patient with severe aortic stenosis and a porcelain aorta died after a transcatheter aortic valve replacement, leading the team to build 3DP models of the aorta to analyze the procedure they executed. To their surprise, they found that using the models changed the surgical plan as it allowed to find the exact position of critical structures and to anticipate difficulties therefore reducing the risk [13].

Besides, many other types of surgeries including Ilizarov method treatment [14], maxillofacial [15, 16, 17], spine and pelvis [18, 19, 20, 21] have been demonstrated to be improved through using 3DP models during surgery planning.

III. Surgical Templates and Guides

The use of 3DP technologies in surgical planning can be further extended to build templates to create patient-specific implants [22, 23] or use such templates as surgical guides [24, 25, 26].

Kozakiewicz *et al.* (2009) obtained computer models of orbital floors from CT scan, mirrored the normal-side to the fractured-side to obtain the target geometry to reconstruct, and then 3D printed the mirrored 3D model. The 3DP model could be used as the template to build shape the titanium mesh for implants [22]. Yu *et al.* (2015) followed very similar steps with the previous case to treat acetabular fractures. From the 3DP model, they could contour the pelvic reconstruction plates and determine the locations of holes of the plates before the surgery [23].

An interesting approach can be found in a computer-aided mandibular reconstruction research from Alma Mater Studiorum University of Bologna, Italy. For mandibular reconstruction, they created three 3DP parts; a 3DP model for surgical planning using acrylonitrile-butadiene-styrene (ABS) plastic, a 3DP repositioning surgical guide using cobalt-chrome alloy, and a 3DP bone plate using titanium alloy. In this reconstruction process, they acquired a vascularized fibula free flap and placed it to the target position, and fixed it using 3DP bone plate using 3DP repositioning surgical guide. Before this surgery, they conducted preoperative training using the 3DP model [24, 25]. In a similar work, Schepers *et al*. (2015) designed a surgical guide equipped with individual screw holes for better accuracy [26].

IV. Orthopedic Reconstruction

Like the above example, another remarkable orthopedic application of 3DP technologies must be orthopedic reconstruction. When it is combined with 3D imaging such as CT and MRI, the processed model can be very effective tool to restore the complex original anatomical structures of a patients.

A few craniomaxillofacial reconstructive surgery using both 3D imaging and 3DP technology was reported e.g., [27, 28]. In [27], the significant portion of skull of a traumatic patient was removed in the process of decompressive craniotomy. A CT scan was conducted to obtain the injured bone structure, and its data was converted to 3D geometric model and prosthesis model using a couple of software, Analyze® (Mayo Foundation, USA), Mimics® (Materialise, Belgium), and Biobuild® (Anatomics, Australia). Clinicians printed the cranial prosthesis with titanium alloy using DMLS 3DP system, and implanted it to the patient successfully. They claimed the advantages of orthopedic reconstruction using 3DP lies with reduced surgery time, the anesthesia time in other word, and less risk of infection [27].

Ocular reconstruction is also a good application of 3DP technology. One study (2014) reported the use 3DP technology to reconstruct ocular orbital walls among 12 patients. They acquired 3D data from CT, mirrored normal healthy side orbit geometry into the defected side to obtain the template, designed implants, and 3D printed using titanium. They could reduce down the surgery time by 25% in average [29]. Such work can be combined with craniomaxillofacial reconstructive surgery as in [30] reported in 2016.

Another application of 3DP must be calcaneal prosthesis [31] (2015). Conventional allograft or autograft reconstruction tends to come with various side effects such as collapse. A custom-made prosthesis was tried in conventional method, but it was reported that the patient suffered from heel pain at the 12-year follow-up [32]. On the other hand, 3DP calcaneal prosthesis could reduce intraoperative refashioning work significantly, and did not result in any major complication or pain after five-month follow-up [31]. Yet it is hard to conclude the superiority of 3DP calcaneal prosthesis due to the short-term follow-up.

More recently, in 2016, a patient with C2 Ewing sarcoma had a surgery to remove the affected region between C1 and C3, and the removed portion was replaced with 3DP implant using titanium alloy [33].

In many applications of 3DP to orthopedic reconstruction, we can find common trend of the process. First, CT modality is dominant due to most of reconstructions are bone segments. Second, mirrored data is utilized if possible. In other words, if the affected part is right, and the left-side is normal, left normal healthy side is mirrored to construct the right-side data. Third, titanium alloy seems most preferred material for the reconstruction.

V. 3DP MATERIALS

All orthopedic treatments require different properties in 3DP materials such stainless steel, titanium, ceramics, and polymers. For example, titanium is preferred most for load-bearing purpose, but it does not have good osteointegration property. However, obviously there are many situations that different demands for biocompatibility, bioactivity, and biodegradability, may not ignored.

One common approach is developing 3DP technology to print material already known as resorbable and osteoconductive as in [34]. Another approach is post-processing the printed object to improve its property. Poly-ether-ether-keton (PEEK) is one of the promising polymers for orthopedic applications due to its strength and biocompatibility. But it does not show good osteointegration, and load-bearing property is not as good as metallic materials. Hence, there are researches to improve its integrating property by manipulating the structural surface or by adding bioactive layer between PEEK and bones [35]. Before that, Pati *et al*. (2015) improved bioactivity of 3DP scaffolds of bone graft substitute using cell-laid mineralized extra-cellular matrix (ECM) that resembles bone microstructure [36].

Meanwhile, researchers started to think biodegradable 3DP implants since they do not require any additional surgery to remove those implants, but its limitation is that the strength of most biodegradable 3DP materials, such as polylactic acid (PLA), is not enough to replace the classical implant materials. Mazzarese (2015) reported that a 3DP fixation screw made of PLA and hydroxyapatite (HA) can be as strong as human cortical bone [37].

VI. EXTERNAL PROSTHESIS AND ORTHOSIS

Most 3DP technologies for external prosthesis and orthosis typically come with 3D scanning technology, which removes the direct contact between the scanning device and the patient. This means measurement can be more accurate to the external view, since any physical contact can induce more or less deformation of soft tissue [38, 39]. In some serious cases, such as patients with skin burns, any assessment with physical contact can be very painful process. Wei *et al*. (2016) generated transparent facemasks using 3D scanning and 3DP technologies to treat facial hypertrophic scars in pressure therapy [40], which could have been a really painful process with the traditional methods.

3DP technologies seems to show clear advantages when the sizes of parts are small, e.g., dental crowns. Many orthodontic researches reported 3DP technologies improve the quality of the prostheses and reduce manufacturing time [41, 42, 43]. Also Ruiters and his colleagues, in 2016, reported their 3DP ocular prosthesis to replace classical impression-moulding to improve dimensional accuracy [44].

As we mentioned earlier, one of the first applications of 3DP technologies was limb prostheses, and more specifically, prosthetic sockets as shown in [3, 4]. In limb prosthetics, prosthetic sockets have always been underestimated parts in their functional importance by non-professionals, while users of prostheses consider they are the most important components. Their design and manufacturing can cause possible pain or earlier fatigue to the users of prostheses. Yet we can find many research works on the design of the prosthetic sockets, including [45].

Not just for the customization issues, 3DP can be a useful tool for delivery. There are significant demands for prostheses in developing countries, due to various reasons such as land mines and cultural issues. However, the delivery system of the prosthetic products from supporting countries to the users in the developing countries has been the real obstacle of the aid [46]. Now there are many designs available in the internet so that the users can manufacture their own prostheses with minimal cost, for example, [47].

On the other hand, orthosis is another promising application of 3DP. Probably ankle-foot-orthosis (AFO) has been considered as the primary orthotic application, since the need for the customization of AFO has been discussed for a long time. AFO mainly characterized by its design, material, and stiffness, and the gait of its user will change by these properties [48]. Depending on 3DP technologies, classical materials used for AFO, such polypropylene, may or may not be used. Therefore, various new materials have been tested for 3DP [49], and at the same time, new design methodology for 3DP has been developed accordingly [50].

But the orthotic applications are not limited to AFO: personalized 3DP footwear insoles [51] were tested for sports activities, and developed 3DP foot orthoses have been developed as well [52]. Even though orthosis to assist human motion has been studied mostly, there are many other orthotic applications using 3D printing.

More interestingly, orthosis (or exactly splints) may be designed for internal organs using 3D imaging. In 2012, University of Michigan successfully installed 3D printed airway splint for a newborn 6-week old baby with tracheobronchomalacia under emergency-use permission. The splint was designed based on 3D imaging data and printed using polycaprolactone since it will be resolved within human body within 3 years [53].

VII. Discussion

Recently various 3DP technologies have been tested in many orthopedic applications, and its feasibility has been proved. Many believes that 3DP will be indispensable technology in orthopedics in the near future.

On the other hand, yet many applications failed to show the superiority of 3DP over the classical manufacturing, and proved no more than the equivalence of the 3DP product with the classical ones. In one recent systematic review (2016), about 20% of 3DP users in surgical applications reported accuracy, manufacturing time, and cost are not satisfactory yet [54].

The accuracy and manufacturing time issues are obviously being resolved rapidly with the development of the technology. Also, these requirements vary significantly depending on the applications. Imanish asserted 3DP reduced manufacturing time of calcaneal prosthesis with five days in total (and one day for 3DP) [31].

Cost issues with materials are being resolved rapidly as stated earlier with the example of [6]. In the case of polymer materials, it seems the cost has been reduced down to the affordable level in the market, especially when the consumption of 3DP material is small enough. Wei [40] reported that their 3DP facemasks cost only 1.5 to 2 times more expensive than the traditional method, partly due to the fact that patients were babies who require significantly less 3DP materials. But it is clear that even this cost is not viable in markets of most developing countries, e.g., reported in [30]. Moreover, the cost of 3DP machines and necessities to technicians to maintain the equipment [55] should be considered as well.

VIII. Conclusions

Orthopedics must be one of the fields mostly actively using 3DP. 3DP is being tested from surgical planning to the implant manufacturing to prove its usefulness. Yet the technology has not overcome the problems arisen 90s completely, those limitations will be removed eventually, when the technological development speed is considered. However, there should be further study to obtain clear advantage to speed up the adaptation of 3D printing technology in orthopedics.

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