iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 9 **Issue:** XI **Month of publication:** November 2021

DOI: https://doi.org/10.22214/ijraset.2021.38712

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International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.429
Volume 9 Issue XI Nov 2021- Available at www.ijraset.com

A Review on: 3D Printed Orthopaedic Cast for Improved Forearm Fracture Rehabilitation

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Abstract: Forearm fracture has many management related problems. In order to regain its function anatomical reduction and immobility is very necessary. Traditional cast is not a satisfactory cast as it is heavy, poorly ventilated and often causes fracture related complications. The paper deals with application of 3D printing technique for suitable cast for forearm rehabilitation. Novel 3D printed cast is light weighted, ventilated, custom fit, strong and waterproof and substantial improvement over conventional orthopaedic cast. With the development in technology, it is expected that the cost of fabrication and its manufacturing time will be greatly reduced in the coming future.
Keywords: bone fracture, immobility, rehabilitation, 3D printing, orthopaedic cast

I. INTRODUCTION

Forearm fracture presents several problems because of complicated structure of forearm. Proper anatomical reduction is important for rehabilitation and any disruption may lead to functional loss of forearm [1,2,3]. The fracture management involve stable fixation of fracture in a proper alignment [4]. Plaster of Paris is the traditional and popular way of immobilising the fracture [5].

Table1. Various Immobilisation Diseases [4]

S.No.	Disease	Example
1	Musculoskeletal Disorder	Fracture, arthritis, osteoporosis etc
2	Neurologic Disorder	Stroke, cerebral dysfunction, neuropathy etc
3	Acute and Chronic pain	Sprains, muscle injury

Plaster cast lacks behind comfort, breathability, skin pressure tolerance, waterproofing option and many other factors for the patient. Technologies like 3D printing, has improved patient care, comfort and satisfaction with new materials [6]. Table1. is the list of some cases where casts or splint are used to immobilise the patient and where 3D printed casts can be used for better rehabilitation.

Traditionally, these fractures have been treated non-operatively, with success in the majority of cases. However, recently, with the advancement of new fixation techniques Traditionally, these fractures have been treated non-operatively, with success in the majority of cases. However, recently, with the advancement of new fixation techniques Traditionally, these fractures have been treated non-operatively, with success in the majority of cases. However, recently, with the advancement of new fixation techniques 3D printing is one of the recent developments in the field of manufacturing technology. This is also known as additive manufacturing process or rapid prototyping. The original name is Rapid Proto Typing machine which were developed to reduce the time cycle for the product development. Now they are known as 3D printing machines. This technology is being used by engineers, doctors, designers, scientists, students, market researchers, artists. There are other three technologies - Computer Aided Design (CAD), Computer Aided Manufacturing (CAM) and Computer Numerical Control (CNC) which are simultaneously developed and evolved. These technologies are required to use 3D printing machine.

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II. 3D PRINTED ORTHOPAEDIC CAST

In 2008 first 3D prosthetic leg was produced [7]. In 2013 Jake and Ollie Evill designed and developed a 3D printed cast and named it Cortex Cast shown in Figure1. [8].

Figure 1. First 3D printed cast [7]

Custom specific features in a cast will increase the satisfaction level and its functional outcome. Currently many 3D printed cast model options are available like Xkelet, Osteoid, Summit ID etc. [9]. Studies have expected the cost of the cast to be around 15,000 – 35,000 INR but it is expected to decrease in coming future [10]. Few of the 3D printed cast are being used in local centres in the USA, Latvia, Brazil and Spain. The main disadvantage of 3D printed cast is the long printing hour and the swelling caused by fracture. As the swelling changes it shapes changes and the fit can become loose therefore this factor should be estimated beforehand and the cast should be adjustable [8].

A. Features of Cast

3D printed cast offers multiple benefits and provide patient satisfaction. It also offers potential for further improvement in its function as well as comfort as new materials are being used. Following are some of the features of the cast which help in speed healing of the fracture:

1) *Functioning Features of Cast:* A cast is used to encase a limb or part of the body to stabilize and hold anatomical structures in place to allow healing of broken bones and ligament tears by promoting immobilization.

a) *Ideal Cast Features:* A cast should fulfil its purpose of immobilising the injury with maximum efficiency. The cast helps in the fracture healing and has increased its functional outcome [11].

- A cast should provide immobilisation,
- A cast should protect the injury
- A cast should decrease the pain
- A cast should allow easy application and removal of cast.

b) *Healing Efficiency of 3D Printed Cast:* To stabilise the fractured arm, a traditional cast is used for 6-7 weeks for healing of the bone. Inaccessibility to the plastered region in the cast causes several fracture diseases. After the removal of plaster physiotherapy of the patient is scheduled to regain the lost strength. With the use of 3D printed cast patient can start their external treatments like cryotherapy, electrical stimulation, therapeutic ultrasound etc. during the time of healing which reduces healing time by 40% and increases the healing efficiency by 80% [12]. Here are some healing therapies which are used and which could be used in a 3D printed cast:

- *Low-Intensity Pulsed Ultrasound (LIPUS):* It is a device that uses low intensity ultrasound to treat fresh fracture and nonunions they accelerate the healing by 38% and 86% respectively. Thus, it heals nonunions more effectively than fresh fractures [12].
- *Chromotherapy:* It is a healing treatment that uses visible spectrum of the electromagnetic radiation to cure diseases. Body is assumed diseased or not functioning when it deviates from expected vibration. It has shown that blue color has anti-inflammatory, anti-itching, anti-irritation, and anti-stress properties and hence can be used for treating them. The color green increases immunity, builds up muscles, bones, and tissues [12].

2) *Additional Features*

a) *Topologically Optimised (TO) Cast:* Topologically optimize material in a given design domain i.e., optimising a design means minimising the weight while maximizing the stiffness. The TO design at 30% volume fraction provide a light weighted and well-ventilated cast. 30% volume fraction means 30% of the material is kept for optimised design. The most common TO method is solid isotropic material with penalization parameterization (SIMP) method which rely on Finite Element Analysis (FEA). This method can successfully and efficiently customize an appropriate fit cast, with less material, and improved ventilation but takes time [13].

b) *Pressure Distribution of 3D Printed Cast:* Traditional cast reports various complications because of unbalanced pressure distribution like cutaneous diseases, compartment syndrome, and vascular comprise. However, wearing pressure is important to maintain the reduction in the treatment of fracture. Novel cast hold the fracture at proper aligned anatomic position with evenly distributed pressure and provide the proper wearing pressure to treat the fracture. This decreases the complication of risk and increases the healing rate [14].

c) *Adjustable Cast:* The custom design offers an appropriate fit but sometimes fracture problems like swelling needs some adjustment, the design hence offers adjustable locking mechanism while maintaining the fit of the cast. although these decisions are made under supervision of doctor [15].

d) *Visibility of a Cast:* Traditional cast does not allow for visual inspection of the fracture. These open 3D printed cast design allow visual inspection of the skin and the wound. Radiological inspection is possible with these cast hence we can keep a check on late fracture complication and avoid them [15].

B. *Designs of 3D Printed Orthopaedic cast*

Designing of a 3D printed custom orthopaedic cast the injured limb involves various steps. Firstly, the injured arm is 3D scanned and then the data file is transferred in a Computer Aided Design (CAD) software then exporting STereoLithography (STL)file, and manufacture using a 3D-printing technique [16]. Figure 2. shows the workflow of the printing of a 3D printed cast.

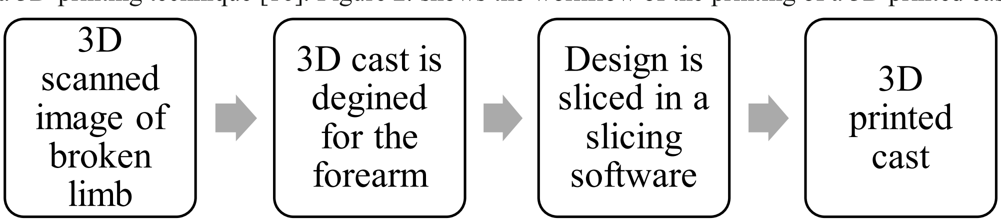

Figure2. Flowchart of designing a 3D printed orthopaedic cast.

3D printing is used for manufacturing the customised product. Every patient is unique and 3D printing can create a functional, comfortable, lightweight and an appropriate fit device. 3D printing manufacturing can produce various complex design product without compromising its strength. A cast can be designed considering numerous factors like problem, mechanical property, feature of the cast etc. Following are the type of orthopaedic cast on various basis:

1) On the Type of Disease or Injury

a) For fracture and Sprain: To heal a broken bone or a muscle sprain currently plaster cast or splints are used. These casts are heavy, and uncomfortable and may cause many complications. The 3D printed casts are light, comfortable and minimises the limitation of the traditional cast. The novel cast has proven to increases the healing efficiency of the injury [14]. To treat a fracture, the cast thickness should be more than or equal to 3mm and for splint the thickness should be between 1-2mm. The limitation with the 3D printing cast is its manufacturing time and cost. The cast can take approximately 2-3 days to print and hence cannot be used in emergency situation [17]. Figure 3(A) and (B). shows a 3D printed cast and splint for forearm and finger respectively.

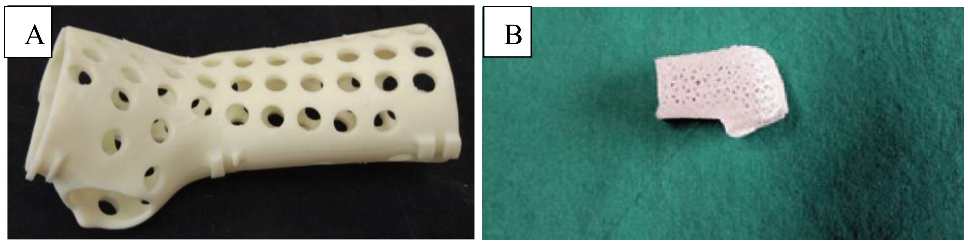

Figure 3. (A) A 3D printed orthopaedic cast for immobilising forearm fracture [18] (B) A 3D printed splint to treat mallet finger [19].

b) For Orthosis and Prostheses: Orthotics is a device that helps in stabilising an affected body part. They are mostly used when a person has to regain its musculoskeletal functionality. Prosthetic helps in enhancing the functionality of a body part. These are used in more severe cases like implants, artificial heart, limb etc. In designing a traditional prosthetic and orthosis device designer is concern about the functioning of the device, but no attention is given to its look which may affect the patient psychology [20]. The device manufactured from 3D printed is custom made with patient specific features. Traditional prosthetic and orthosis take a long time to manufacture whereas additive manufacturing takes 2-3 days to manufacture the device. Figure 4(A) and (B). shows a 3D printed lower leg orthosis and hand prostheses respectively.

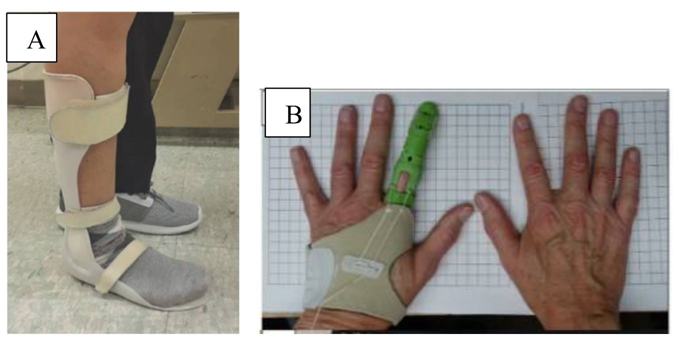

Figure 4. (A) A designed and tested 3D printed lower leg orthosis [21] (B) A 3D printed hand prostheses [22].

2) On the Basis of Type of Material Used

a) Polylactic Acid (PLA): PLA has high strength and is also low in cost. The material is biodegradable and biocompatible hence skin friendly. PLA has low temperature resistance 50º-60ºC and lower chemical resistance. The low temperature resistance limits its use in high temperature region. All Fused Deposition Modeling (FDM) machines can process PLA easily. It is recommended for regular user and with no dynamic loading prediction [8].

b) Acrylonitrile Butadiene Styrene (ABS): It has high impact resistance and is resistant to any temperature encounter in day-to-day life. ABS is neither biocompatible nor biodegradable and costs slightly higher than PLA. ABS is processed by small number of 3D printer but it can be used in dynamic loading condition [8].

c) Nylon Polyamide-12 (PA12): Nylon is a hard to manufacture and expensive material. It is highly resistant to temperature and chemical. It has high bending strength and high impact and scratch resistance. It is biocompatible and mildly environment friendly. It can bear high loads and dynamic loading condition [8].

ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.429
Volume 9 Issue XI Nov 2021- Available at www.ijraset.com

3) On The Basis Of Layer Of Cast

a) Single Layer: The single layer cast are the most commonly manufactured novel cast. They have one single layer to protect and immobilise the fractured bone. It is stiff and provide further protection to the injury. Personalised 3D printed orthopaedic cast are comfortable and easy to use. These cast has largely improved the functionality compared to the traditional cast. The cast are well ventilated and provide visibility for inspection of the injury. These are custom fit, well ventilated, lightweight and adjustable [14, 23]. Figure 5 shows a 3D printed orthopaedic cast.

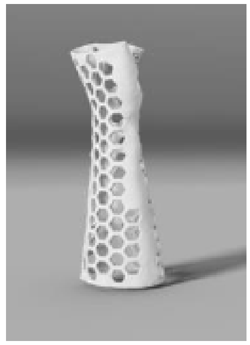

Figure 5. Single layer 3D printed cast [24].

b) Double Layer: The double layer cast consist of two layers. The outer layer is the rigid layer provide strength and protection to the injury. The inner layer is the flexible layer which provides appropriate fit. The two-layer cast provide a constant fitting to the injured limb during the healing process. Shape deformation is an additional parameter considered in the account for swelling of the injury. Assembling will be impracticable if the inner flexible layer is too complex. The manufactured cast is both flexible and stiff advantageous for patient increasing the efficiency [23]. Figure 6. shows a 3D printed double layer cast.

Figure 6. Double layer 3D printed cast [23].

C. Clinical Study of 3D Printed and Plaster Cast for Mallet Finger

The alternative cast are an option as they are stronger, open design and used 3D scanner to measure the fracture data for the design of customise cast [19]. Clinical study performed on 3D printed cast and plaster cast performance of patient satisfaction with both casts, a satisfaction evaluation named (Quebec User Evaluation of Satisfaction; QUEST) and a wearability evaluation (Product Performance Program; PPP) was supervised. Both were rated on a scale of 5 where 5 was highest and 1 was the lowest. In the satisfaction evaluation the 3D printed cast showed similar and satisfied result compared to plaster cast with and average value of 4.75 and plaster cast having value 3.5 i.e., higher but comparable. However, in the wearability evaluation the plaster cast received many non-applicable ratings compared to 3D printed cast the plaster cast was rated 1.70 and the 3D printed cast was rated 4.82 this was nowhere comparable. The PPP evaluation showed that 3D printed cast allows accurate, rapid production of customised orthoses, an improvement in existing production methods [19]. These casts produced have wider prospective only when these casts are clinically approved and brought in practice [14]. The casts tailor fitting factor is the most advantageous for patient and this factor force it for clinical use. With the technological improvement it is expected to improve in the next few years [15].

Table 6 Clinical comparison of 3D Printed cast and plaster cast [19].

Test	Evaluating factors	3D Printed Cast	Plaster of Paris
Satisfaction Evaluation	Dimension	5	3
	Weight	5	3
	Adjust	5	3
	Safety	5	3
	Durability	5	3
	Ease of Use	5	5
	Comfort	4	3
	Effectiveness	4	4
Total Score		4.75	3.5
Wearability Evaluation	Likely to use	5	4
	No complication while using	5	0
	Can be used anywhere	5	0
	Simple wearing procedure	5	0
	Easy principle of cast	5	5
	No risk of malfunction	5	0
	Incorrect use causes damage	5	0
	Comfortable to wear	0	0
	Little effort required to wear	5	0
	No requirements when using it	5	0
	Easy to use finger while wearing	5	5
	Adequate size and shape to protect finger	5	3
	Portability	5	0
	Good color and shape	4	2
	Easy to clean and care	5	2
	Not causes skin problem	5	3
	Cast strength	5	5
Total Score		4.82	1.70

Hence, not only 3D printed casts are more effective but they are skin friendly and can be used for long duration without any skin complications [15]. These casts are pleasant to look at and X-ray of the fractured limb can be taken easily during the time of healing. To speed the healing time ultrasound can also be encouraged [12]. With the growing patient care experience further improvement is more consistent and a stable alternative to the current method for casting.

D. Limitations

The novel cast has many benefits over traditional casts but there are few disadvantages of the cast like:

a) *Scanning:* Data of the fractured arm is obtained by using 3D scanner. Scanning the arm is a difficult process to conduct as patient must keep their arm still till the scanning is done which may take several minutes. Holding the hand can be painful and difficult for patient hence there is a need of more developed 3D scanners [14].

b) *Long Printing Hours:* It is one of the most significant disadvantages of 3D printed cast. Normal printing time of a cast is 3-9 hours or even more depending on size and complexity of the cast. Long printing hours can cause strain on patient and will affect the capacity of hospital for treating acute fracture. Hence, this disadvantage disqualifies the cast for mass production [15].

c) *Cost:* The manufacturing cost of a novel cast is relatively higher compared to the traditional cost. The rapid growing technology will reduce the manufacturing cost in coming future. This will make the cast clinically feasible and its application widespread [10,14].

III. RESULTS AND DISCUSSION

The parameters used to define an orthopaedic cast are that it should be safe and fully functional, with traditional immobilization techniques we have achieved these qualities but these cast develop many skins disease as well as bone injury because of its structure. These functions are fully achieved by novel cast which offer additional benefits like skin pressure tolerance, custom fit, light in weight, ventilated and patient specific. These cast can avoid problems like compartment syndrome, burning of soft tissue, pressure sore, muscle loss etc. There are number of orthopaedic rehabilitation devises which can be used for various disease. A lot of design options are available in 3D printing because of its flexible nature. Though these cast have problems like long printing hour and high cost but with the future development of technology the growing number of freeware and open-source CAD software will be able to connect with low-cost hardware with no skill required.

IV. CONCLUSIONS

The study shows that 3D printed orthopaedic cast has many benefits like it keeps the environment dry and reduces the risk of cutaneous complications. It is a lightweight and at the same time have great strength. With the rapid development of 3D printing in the field of medicine it is possible to manufacture complex structure with cost effective benefits and reduced manufacturing time. Therefore, patient specific casts can be made with this technology helping them to heal faster since they are appropriate fit. Though it has a long list of advantages over conventional cast but its two disadvantage holds it growth in the field, long printing time and cost of the cast. This is because 3D printing is still a growing technology. The rapid growth of technology will reduce the time of production and cost of cast in coming future.

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