NATURAL FIBER REINFORCED COMPOSITES FOR PROSTHETIC SOCKETS

Abstract

Over time, numerous fiber-reinforced polymeric composites have replaced earlier prosthetic materials such as wood, leather, metal, and plastic. We are enthusiastic about the future advancements of prosthetic limbs because of promisingly fruitful research in this area. The development of natural composites and design of socket-based prostheses in relation to the amputee's comfort and mobility for lower limb prosthesis applications were reviewed in the current study. In the present review, we accumulated various mechanical properties of many natural fiber reinforced composites. We also presented the benefits of the natural fiber reinforced composites in prosthesis applications. Design of prosthetic socket was also focused in the present study. We also discussed typical fabrication methods of prosthetic sockets. The study looked at the possibility of substituting current natural composites with naturally generated fibers. Recent trends in nanoparticles, nanotechnology and their advantages in prosthetic applications have also been illustrated. Despite having extremely strong mechanical qualities, synthetic fibres are excessively expensive and emit carbon dioxide during processing, whilst synthetic materials tend to contaminate the environment after being used. Therefore, research into natural fibre reinforced polymer matrix composites may become a future trend in order to provide prosthetic sockets that are inexpensive for disabled people who are less well off financially and for short-term use. Consequently, there is a greater chance that biocomposite made from naturally occurring materials may replace such composites and plastics.

Keywords: FRPC; natural fiber; composite; prosthesis; liner; moulding; casting; strength.

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I. INTRODUCTION

Recently, due to its greater specific strength and stiffness, long durability, high fatigue resistance, non-corrosive nature, and reduced weight, polymeric composites have become the most important and intriguing materials for a variety of applications[1]. Fiber-reinforced polymeric composites (FRPCs) have taken the place of older prosthetic materials such wood, leather, metal, and plastic over time. Orthopaedic equipment is crucial for granting the disabled a certain amount of freedom and ensuring their professional and social inclusion[2].The main three primary parts that make up transtibial prostheses are a foot, a pylon, and a socket. Many prostheses especially, socket is made of compositematerial reinforced with synthetic fibres like carbon or glass fibres in the polymer matrix[3].Such fibres are expensive because of their great mechanical qualities, especially in nations where these synthetic fibres are imported[4]. Sadly, some amputees still cannot afford the cost of the prosthetics.The kind and quality of the materials used to create a prosthesis directly affect its price, and choosing inexpensive materials can increase the number of individuals who can utilise such prostheses, especially in developing countries.It is now essential to explore for local alternatives to fibres that keep the same mechanical properties while being more cost-effective than those used in standard sockets.Given their mechanical capabilities, light weight, and cost-effectiveness, natural fibres are currently the subject of expanding international research that aims to incorporate them into composite materials[5, 6].

II. NATURAL FIBERS REINFORCED COMPOSITES

Plant-based fibres and animal-based fibres are the two primary divisions of natural fibres, which are made from renewable resources like plants, animals, and minerals. Plant fibres can be found in a variety of materials, including bamboo, coconut fibre, flax seeds, cannabis sativa, vegetable fibre, straw, nettle, ramie, wood, grains,cotton, hemp, jute, and so on. The zoological fibres such as, wool and silk are kind of natural fibres derived from animal sources and all the animal fibres are made of proteins. The natural fibres are being converted as appropriate for prosthetic sockets because of their intrinsic strengths and weaknesses. In order to provide support, comfort, and a reliable connection between amputated limbs and artificial limbs, prosthetic sockets are essential interfaces.Synthetic polymers and metals are common components of conventional socket materials, however new discoveries in materials science have inspired scientists to look at biocompatible and environmentally friendly options. Numerous advantages of natural fibres include their light weight, breathability, biodegradability, and hypoallergenicity. Natural fibres with strong tensile strength and elasticity, such as cotton, flax, hemp, and jute are bering considred to make prosthetic sockets. Wool from sheep has natural insulating and cushioning qualities, whereas silk from silkworms is lightweight and silky. These fibres can be used alone or in combination to build composite materials that make the best use of each fibre type's advantages.

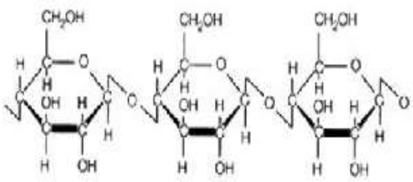
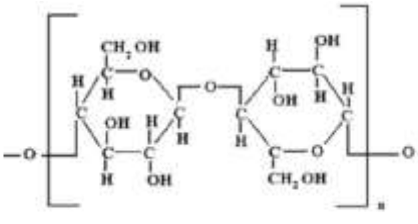
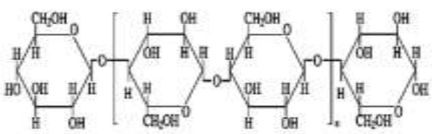
The prosthetics industry has made substantial improvements in both materials and design recently, and the incorporation of natural fibres into prosthetic sockets has drawn attention. Natural fibres are an appealing choice for improving the functionality and user experience of prosthetic sockets because they provide a special combination of qualities, such as biocompatibility, light weight, and sustainability. These fibres, which can be divided into plant-based fibres and animal-based fibres, are produced from renewable resources such as plants, animals, and minerals.’

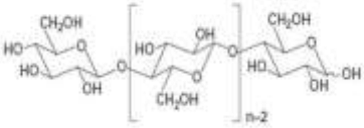
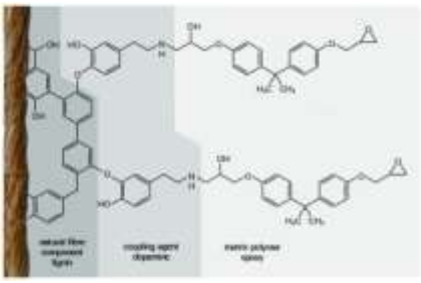
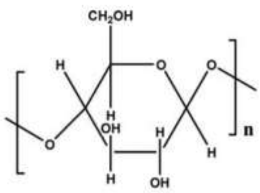
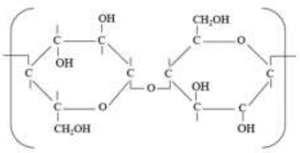
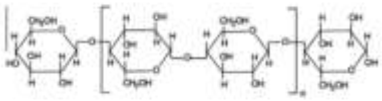
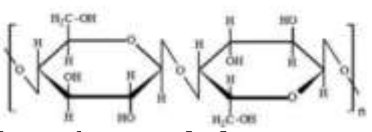
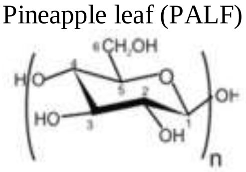
Biocompatibility, light weight, energy absorption, sustainability, and thermal regulation are benefits of natural fibre composites. While the lightweight nature increases overall comfort, biocompatibility lowers the possibility of allergic responses or pain. Energy absorbing qualities enhance gait dynamics and lessen stress-related injuries by minimising the effect on residual limbs when moving or running.

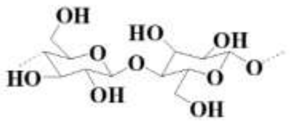
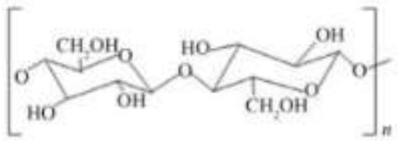
Sustainability is consistent with sustainable practises, which helps natural products have less of an impact on the environment than synthetic ones. Natural fibres frequently provide better moisture-wicking and breathability qualities, enabling better temperature and moisture regulation inside the socket. However, natural fibres face difficulties with standardisation, moisture absorption, processing methods, and durability.

Due to their outstanding stiffness-to-weight ratio, flax fibres have been investigated as a potential material for prosthetic sockets in case studies. In order to create a comfortable interface between the residual limb and the socket, a hybrid composite made of cotton and silk fibres has been studied for its softness and biocompatibility.Mechanical proprties of various natural fibers reinforced composites are illustrated in **Table 1**. Ultimate tensile strength properties of the plant oil resin and natural fiber composites are depicted in **Figure 1**[3]. A recent trend in nanoparticles/nanotechnology and their advantages in prosthetic applications is illustrated in **Table 2**.

Table 1: Important Mechanical Properties of Various Natural Firber Composites

Sl. No	Natural Fibers and Chemical Structure	Matrix Polymer and Content (%)	Flexural Strength (MPa)	Tensile Strength (MPa)	Impact strength (J/m)	Ref.
1	Ramie-stockinett  Chemical structure[7]	Plant oil resin; 90%*	-	80.8	-	[3, 8]
2	Jute  Chemical structure[9]	Polypropylene (PP); 80%*	45	24	40.13	[8, 10]
3	Sisal  Chemical structure[11]	PP; 70%*	20	35	58	[8, 12]

Sl. No	Natural Fibers and Chemical Structure	Matrix Polymer and Content (%)	Flexural Strength (MPa)	Tensile Strength (MPa)	Impact strength (J/m)	Ref.
4	Hemp  Chemical structure[13]	PP; 70%*	33	18	39.62	[8, 14]
5	Flax  Chemical structure[15]	PP; 70%*	43	25	-	[8, 16]
6	Coir  Chemical structure[17]	PP; 70%*	50.532	26.616	24.32	[8, 18]
7	Banana  Chemical structure[19]	PP; 70%*	48	45.25	46.03	[8, 20]
8	Kenaf  Chemical structure[21]	PP; 70%*	58	46	-	[8, 22]
9	Cotton  Chemical structure[23]	PP; 70%*	145	35.3	-	[8, 24]
10	Pineapple leaf (PALF)  Chemical structure[25]	Poly vinyl alcohol (PVA); 60%*	-	33	-	[8, 26]

Sl. No	Natural Fibers and Chemical Structure	Matrix Polymer and Content (%)	Flexural Strength (MPa)	Tensile Strength (MPa)	Impact strength (J/m)	Ref.
11	PALF	Polyester (PS); 50%*	53.02 ± 1 .20	69.12	65	[8, 27]
12	PALF	Epoxy; 50%*	81.27 ± 1 .27	80.12	48	[8]
13	Bamboo  Chemical structure[28]	PP; 50%*	49.56	28.95	27.32	[8, 12, 29]
14	Water hyacinth  Chemical structure[30]	Methyl methacrylate (MMA); 30%*	-	47.19	-	[8, 31]
15	4perlon/3Cotton/2Carbon	Poly methyl methacrylate (PMMA); 70%#	-	143	-	[32]
16	4perlon/3Flax/2Carbon	PMMA; 65.53#	-	423	-	[32]

* Weight fraction (%), # Volume fraction (%)

Table 2: Recent Trends in Nanoparticles/Nanotechnology and their Advantages in Prosthetic Applications

Sl. No.	Nano Reinforcement	Application	Nano Technology	Advantages	Ref.
1	Carbon-based materials, inorganic nanomaterials	Wearable health monitoring systems	Microelectro mechanical systems (MEMS)	The newest generation of personal telemedicine devices uses biological signals and is driven by developments in materials science, chemical analysis, and manufacturing techniques.	[33]
2	Carbon Nano Tubes /Poly ethylenedioxyt hiophene, poly styrene sulfonate	Fabric-sew able wearable strain sensor	Sensors	The strain sensors showed great linearity of 1000% in 63 ms, high resolution of 0.05%, and high capacity to stretch up to 1275%.	[34]

Sl. No.	Nano Reinforcement	Application	Nano Technology	Advantages	Ref.
3	Metal polymer carbon material (metal-polymer mixture)	Prosthetic limbs for pain relief, Sports prosthesis, Cognitive nerve prosthesis	Hybridization	By combining polymers, graphene, and carbon nanotubes in hybrid composites, neuroprosthetics may enhance neuroengineering.	[35]
4	Silver Nanoparticles	external biomedical device	Photochemical Method	The development of a polymer composite incorporating AgNP for prosthetic liners to address skin issues in patients using external lower limb prostheses	[36]
5	Nano SiO_2	Artificial Socket Prostheses	Artificial neural network technique	Nano particle materials have been used in prosthetic sockets to enhance their mechanical properties and fatigue strength, showing a 60% increase in strength.	[37]
6	Hybrid Nanoparticles (SiO_2, Al_2O_3)	Artificial Socket Prostheses	Nano weight fraction effects	The mechanical and fatigue properties of composite materials used in artificial socket prostheses can be increased by 35% by combining two hybrid nanomaterials.	[38]
7	Walnut shells Nano-powder (WSP)	Neuroprosthetics, neural electrodes was metals.	Vaccum Molding Technique	When made with vacuum moulding techniques and organic materials such nanoparticles, walnut shells and HF, composite prosthetic materials for socket applications shown notable mechanical advantages.	[39]
8	Jute plus carbon	Prosthetic socket	Vacuum bagging process	The mechanical properties of the prosthetic socket (particularly the	[40]

Sl. No.	Nano Reinforcement	Application	Nano Technology	Advantages	Ref.
				flexural modulus and maximum shear stress) are improved by the strengthening layer.	
9	Multiwalledcarbon nanotubes	Sensing robots and soft robotic	Hydrofinished oil-based softener	The conducting elastomer performed brilliantly as a movement detector thanks to its low electrical percolation threshold and improved mechanical characteristics.	[41]
10	Graphene oxide (GO), Zinc Oxide (ZnO)	Coating in automotive, aerospace	Co-precipitation method	The neat natural rubber (NR) and NR-GO nanocomposites' mechanical and dielectric properties were significantly improved.	[42]

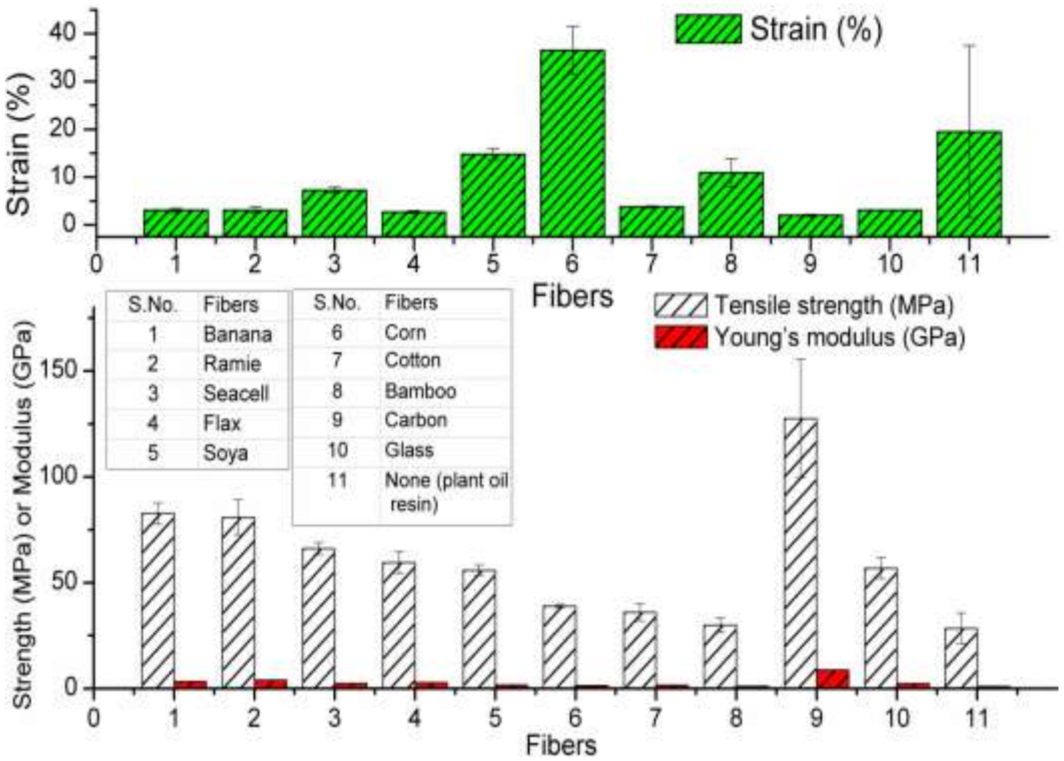


Figure 1: Ultimate Tensile Strength Properties of the Plant Oil Resin and Natural Fiber Composites

1. **Benefits of Natural Fiber Reinforced Composites:** Fiber-reinforced composites are the best biomaterials for prosthetic limb applications because they have a flexible shape and are less heavy, providing superior specific strength and stiffness than traditional biomaterials. However, building a cost-effective prosthesis for weaker people for temporary uses is difficult due to the cost and availability of biomaterials. Due to their availability, lighter weight, cost-effectiveness, biocompatibility, and biostable characteristics, organically generated biocomposites are the most promising biomaterials for constructing prosthetic sockets[43].On the other hand, hybrid composites also have shown excellent mechanical properties without much compromising of biocompatibility. The benefits of hybrid flax and cotton fibre reinforced PMMA composites had shown a workable alternative for prosthetic sockets[32]. The results can be utilised to direct future lower limb prosthesis research and development, especially for those composed of natural fibres.According to the study, 4perlon/3Flax/2Carbon (FC) composite had the highest densities, thicknesses, and volume proportions. By modifying the material and using assembly prearrangement, the tensile strength was raised to 423 MPa. Three flax layers and two layers of carbon produced the highest tensile modulus values (5.6 GPa). The highest percentage of elongation values was 7.9%, obtained by three cotton fibres and two layers of fibreglass[32]. According to numerical and experimental results, the laminating flax and carbon below-knee prosthesis created amazing safety aspects because of its extended life design.The theoretical safety factor is a ratio of experimentalfailurestrength to vonMisesStress whereas failure index is calculated by ratio of von Mises stress to experimental failure strength[32].

   A typical comparison of natural fiber composite-based socket over other synthetic and conventional socket materials is illustrated in **Table 3**[https://atira.in/wp-content/uploads/2023/05/table-685x1024.png].

Table 3: Comparison of Natural Fiber Composite-Based Socket Over Other Synthetic and Conventional Socket Materials

Sl.No.	Various Aspects of Sockets	Natural Fiber Composites	Conventional Sockets	Synthetic Fiber Composite Sockets
1	Strength	Fulfills the desired strength	Depending on the subject material	More robust tensile strength
2	Comfort	Lowers pressure points, absorbs shocks, and provides cushioning effect.	May lead to pressure points and pain	Cushioning is provided, but natural fibres may be more beneficial in this regard
3	Weight	Low in weight	Heavy potential	Depends on the type of fibresutilised
4	Durability	Extremely durable	maybe prone to deterioration with wear and tear	Depends on the type of fibresutilised

Sl.No.	Various Aspects of Sockets	Natural Fiber Composites	Conventional Sockets	Synthetic Fiber Composite Sockets
5	Customization	Simple to alter and mould to fit a person's remaining limb	Few possibilities for customization	Simple to mould and customize to fit a person's residual limb
6	Biocompatibility	Excellent, lower chance of allergies or skin irritation	Could trigger allergies or skin rashes	Some people could be sensitive to synthetic fibres
7	Moisture Control	Characteristics that wick away moisture keep the surroundings breathable and dry.	Possibly lead to perspiration and skin-related problems	It's possible that synthetic fibres don't manage moisture as well.
8	Sustainability	Derived from sustainable resources, green	petroleum-based and less environmentally friendly	Primarily petroleum-based and less environmentally friendly
9	Cost	Potential savings from low-cost raw materials	Can be pricey	Due to higher production expenses, can be more expensive

2. **Design of Prosthetic Socket:** A schematic design of standard prosthetic limb socket is illusrtated in **Figure 2**[3]. The use of plant-based polycarbonate-polyurethane copolymer resin and plant fibre composite in the creation of prosthetic limb sockets was examined in a study by Campbell *et al.*,[3]. Banana and ramie plant fibres can be mixed to produce a strong composite material, according to tensile strength testing.Two of the four test sockets that were constructed and tested failed at loads greater than that for normal materials. The ramie stockinette weave, which adds to the durability of the socket, is responsible for its thicker wall. Another factor in the failure of the socket is the quality of the interfacial bonding between the fibres and the resin. The plant resin and ramie fibre composite socket has the potential to take the place of the conventional layup in the production of prosthetic limb sockets, according to the findings of this study.

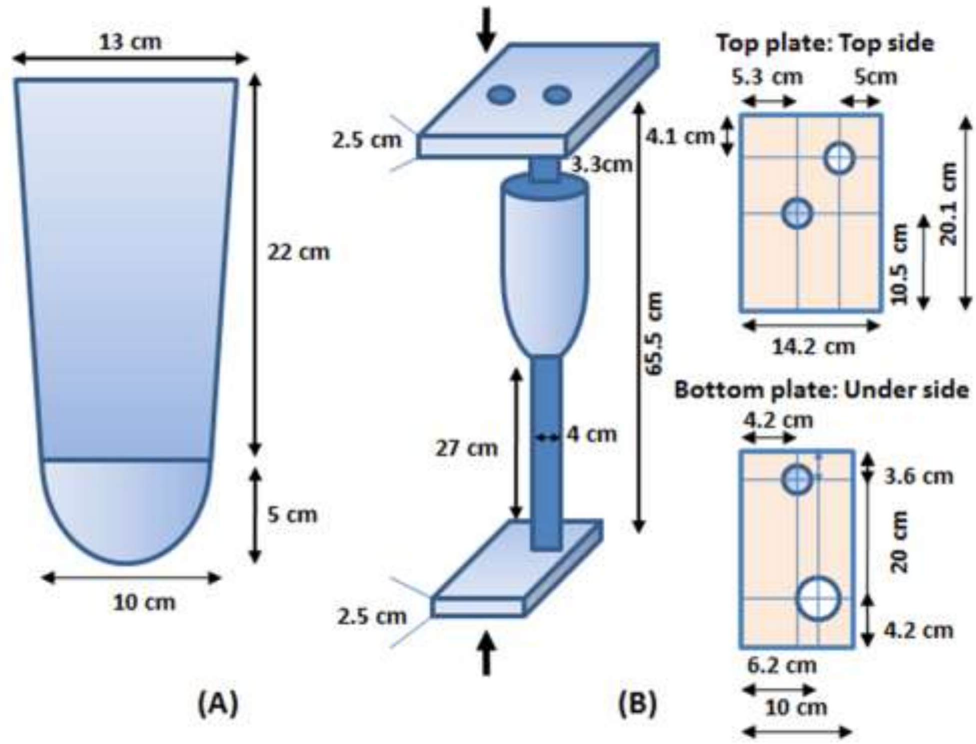


Figure 2: Schematic design of (a) the standard socket and its measurements were created based on a socket with a flat distal end (indicated) that is detailed in ISO 22523, a curved distal end offers the pyramid connector a superior mounting surface; and (b) details on the socket and test jig's components, sizes, and construction. Ball and socket joints are used to apply compression force in the two arrows' directions. A ball socket-forming indented zone is indicated by the shaded area on the top and bottom plates.

In order to design a suitable prosthetic limb, thermal comfort on prosthesis socket should be considered. Thepressure distribution analysis in a transfemoral prosthetic socket is cruical in this applications [44].The evaluation of a de facto approach for the installation of sensors can be broken down into four main categories: (i) selection of sensor, (ii) sensor location, (iii) sensor integration, and (iv) data display, as depicted in **Figure 3**[45].For experimental studies on the effects of intra-socket pressure sensors, transfemoral amputees can adopt a de facto methodology. The argument that pressure sensors would be more likely to lead to associated sensor design advancements if they were created in close collaboration with other types of sensors and with people who have a thorough understanding of prosthetics. The production of free research data and increasing multidisciplinary collaboration would support this de facto approach study[45]. The kind of natural fibre used, the thickness of the socket, how well it fits, and the wearer's level of activity are some of the variables that can impact the heat and pressure distribution on a natural fibre prosthetic socket.

- **Natural Fibre Type:** The thermal characteristics of various natural fibres vary. For instance, hemp and flax are better insulators while bamboo is a significant heat conductor.
- **Thickness of the Socket:** The thickness of the socket will increase insulation and help to lower heat buildup.

- **Fit of the Socket:** The socket's fit should be perfect to uniformly distribute pressure and prevent hot spots.
- **Wearer Activity Level:** More active people will produce more heat and may be more prone to feel pain from a natural fibre socket.

A natural fibre prosthetic socket can be used in a number of ways to lessen the possibility of temperature and pressure pain. These consist of:

- Making the socket thicker.
- Using a liner with rhe socket.
- Modifying the socket's fit.
- Steering clear of activities that produce a lot of heat.

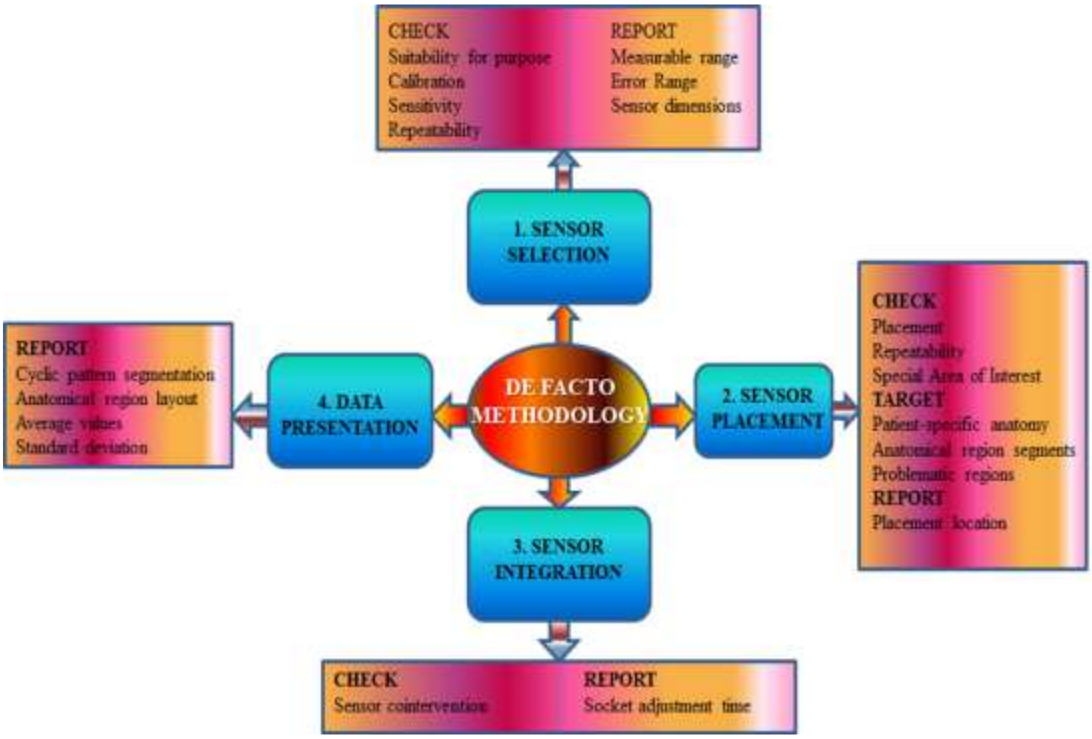


Figure 3. Evaluation of a de facto approach for the installation of sensors in the prosthesis.

Many amputees experience temperature stress in their daily lives since it can negatively affect how comfortable and effective a prosthetic device is to operate.

The barrier in the prosthetic socket causes a number of issues, such as conduction, evaporation, and radiation. Skin rashes can develop on amputees as a result of the warm environment in the side prosthetic socket.

3. **Fabrication of Prosthetic Socket:** In broader sense, two main methods followed to fabricate the prosthetic sockets are molding technique [46, 47] and castingtechnique[48, 49]. In molding, the patient's stump is cast in a negative mould, which is then used to make the socket. Vacuum forming is the most typical type of moulding for prosthetic

sockets. On the other hand in casting,a positive cast of the patient's stump is used, and the socket is subsequently made using that cast. Plaster casting is the most typical type of casting used for prosthetic sockets.

The following processes are needed to create a prosthetic socket using the ***moulding technique:***

- Make the stump ready. The stump needs to be hair-free, clean, and dry.
- The stump should be cast in negative form. Vacuum forming or another moulding method can be used for this.
- Make the socket material ready. The socket material needs to be precisely sized and shaped.
- Warm up the socket material. A heat gun or oven can be used for this.
- Over the negative mould, place the heated socket material.
- To harden, let the socket material cool.
- From the negative mould, remove the socket.
- The socket's fit should be adjusted. It might be necessary to cut the socket or add padding for this.

The procedures for creating a prosthetic socket using the ***casting method*** are as follows:

- Make the stump ready. The stump needs to be hair-free, clean, and dry.
- Cast the stump in a favourable light. Plaster casting or another casting process can be used for this.
- Make the socket material ready. The manufacturer's recommendations should be followed while mixing the socket material.
- Fill the positive cast with the socket material.
- Delay the curing of the socket material.
- From the positive cast, remove the socket.
- The socket's fit should be adjusted. It might be necessary to cut the socket or add padding for this.

Apartform those two basic technqiues, the prosthetic limb socket can be made of some advanced technologies including, selective laser sintering[50], 3D printing technology[51], and so on.In addition, the prosthetic liner with embedded sensor technology can be used in the prosthetic socket to monitor the pressure and/or thermal disribution[52].

The technique of manufacturing chosen relies on the patient's and prostitute's unique needs. Casting is typically chosen due to its flexibility and capacity to produce unique sockets, but moulding is typically preferred due to its speed and accuracy.The unique requirements of the patient and the prosthetist determine the fabrication procedure that is used. In general, casting is favoured because of its flexibility and capacity to produce bespoke sockets, whereas moulding is favoured because of its speed and accuracy.

4. **Safety Tips in Fabricating Prosthetic Sockets:** During creating prosthetic sockets, the following safety advice:

- When working with resins or plaster, always wear personal safety equipment (PPE), such as gloves, goggles, and a respirator.
- Plaster and resin can be dangerous if consumed or inhaled.
- Plaster and resins may also irritate the skin.
- When working with resins or plaster, always work in a well-ventilated location.
- Avoid working with plaster or resins close to heat sources or open flames.
- When creating prosthetic sockets, you can assist avoid mishaps and injury by keeping in mind these safety precautions.

III. CONCLUDING REMARKS

The use of natural fibres in prosthetic sockets is a noteworthy advancement in the field of prosthetics. These fibres improve consumers' comfort, functionality, and overall quality of life by offering benefits like breathability, moisture wicking, and biocompatibility. Because of the prolonged usage and interaction with the residual limb, these qualities are crucial in prosthetic sockets, which call for materials that prioritise user safety. Since natural fibres are lightweight and manageable, users may go about their daily activities more comfortably and confidently.

Due to their flexibility, these fibres can conform to the contours of the residual limb, which enhances stability, proprioception, and weight distribution.However, problems with long-term wear and durability need for creative engineering and material science. It's critical to achieve a balance between the need for durable prosthetic solutions and the ecological benefits of natural fibres. The use of natural fibres in the creation of prosthetic sockets represents a development in user-centered, ecologically sustainable, and technologically advanced prosthetic solutions.

Natural fibres are expected to be employed in prosthetic sockets in more sophisticated and effective ways as research and development go forward, improving the lives of people who have lost limbs and reaffirming the commitment to enhanced mobility, comfort, and overall wellbeing.

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