The Capability of Lyocell/EcoPoxy Braided Composite in the Creation of a Prosthetic Socket

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Abstract Prosthetic sockets are widely known as the most important part of a prosthetic. In this study, the feasibility of lyocell/EcoPoxy braided composite is examined in its use in a prosthetic socket. By comparing different known physical properties of lyocell/EcoPoxy to materials normally used, such as carbon/epoxy, fibreglass/epoxy, and polypropylene, it has been found that lyocell/EcoPoxy has the physical properties to be used as a material for prosthetic sockets.

Introduction Worldwide there are millions of people who are left amputees after a war, a conflict, a natural disaster, a chronic disease, thromboembolism or arteriosclerosis [1]. It has been reported that up to 80% of people in developing countries are in need of care due to amputation; this means that about 3 to 4 million people in the developing world need a prosthesis, although these estimates are conservative. It is important to keep in mind that economic, social, cultural, psychological, religious, technological, and other factors have a great effect on the accessibility of prosthetics [2]. The socket of a prosthesis is often regarded as the most important part of a prosthetic; the socket is the primary interfacial point between the stump and the prosthetic. Unfortunately, the socket can often create discomfort leading to soft tissue damage, blisters, and ulcers, this can affect performance, biocompatibility and versatility inhibiting the ability to live normal life [3].

Polypropylene is often used in prosthetic sockets; however, plastic can cause increased discomfort for the user [4]. Also, with the increased efforts of the materials industry to reduce their environmental footprint it is important to find both economical and ecological alternatives. This has led researchers to turn to biological composites, using fibres such as banana, ramie, cotton, bamboo, and flax with resins such as plant oil resin. Such composites provide the ability to transmit forces to the reinforcing fibres within them. The fibres are capable of supporting forces along their entire length, which proved useful in stabilizing pressure applied to the prosthetic [5]. As of yet, no biological options have been found to replace carbon or glass fibre with equal elasticity and tensile strength. Therefore, there is a need for biological plant fibres to not only be inexpensive, recyclable, abundant and renewable but also durable with high strength, low bulk density yet with a high strength to weight ratio.

2D braiding uses a fibre, such as carbon and overlaps the material, which eventually is impregnated by resin, to allow for a material that is strong and light. Braiding has provided benefits such as allowing for more manufacturing consistency, allowing for improved fibre alignment and easing the process of producing composites from complex mould shapes with more drapability. Due to the overlapping nature of braids, it allows for increased resistance to through-thickness loads. By tailoring the angle it can be manipulated to be most suitable to the loads needed to be taken on. Despite braided

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composites' possibility for high success, little research has been done on the ability of green-braided composites to be used in prosthetics, specifically when looking at lyocell fibres (commercially known as Tencel) and from the matrix EcoPoxy. This study examines the capability of lyocell/EcoPoxy braided composite in the creation of a prosthetic socket.

Methods and Results Lyocell fibres are beneficial as they can be characterized by their uniformity, high purity, and reproducibility of the fibres, this allows for a high potential for success. As well, lyocell is considered to be environmentally friendly due to its ability to be renewed and due to manufacturing an organic solvent called N-methyl morpholine N-oxide, which can be reused [6]. EcoPoxy (BioPoxy 36) is a bio-resin that has greater stiffness and higher elastic modulus then most other eco resins making it more reliable in use [7]. However, unfortunately, EcoPoxy only is 36% bio-based, however, compared to a conventional resin this is still more favourable to the environment [8]. These characteristics allow for great potential to make a braided composite for use in a socket. Table 1 displays approximate values for the elastic moduli of lyocell/EcoPoxy, the shear modulus, and the Poisson's ratio, as calculated using the following equations:

Equations for Determination of Properties of Lyocell/EcoPoxy

$$E_{11} = V_f E_f + V_m E_f$$

$$1/G_c = V_f/G_f + V_m/G_m$$

$$1/E_{22} = V_f/E_f + V_m/E_m$$

$$V_{12} = V_f \nu_f + V_m \nu_m$$

E_{11}= longitudinal elastic modulus E_{22} = transverse elastic modulus

V_f= fibre volume fraction E_f = transverse elastic modulus of fibre

E_f= longitudinal elastic modulus of fibres E_m = transverse elastic modulus of matrix

E_m= longitudinal elastic modulus of matrix V_m= matrix volume fraction

G_c= shear modulus of composite G_m = shear modulus of fibres

G_m = shear modulus of matrix ν_m = poisson's ratio of matrix

ν_f = poisson's ratio of fibre

Figure. 1

These values allowed for the discovery of the shear modulus, transverse elastic modulus, longitudinal elastic modulus, and the Poisson's ratio of lyocell/EcoPoxy[9]

Giving the results in Table 1 and from other sources.

Properties of Materials Used in Prosthetic Sockets

Table 1	E-Glass/Epoxy [10,11]	Carbon/Epoxy [12,13]	Polypropylene [14]	Lyocell/EcoPoxy [15,16,17]
E_{11} (GPa)	40.3	126.9	8.25	59.932
E_{22} (GPa)	6.21	11.0		3.79
G_{12} (GPa)	3.07	6.6	0.920	2.52
Poisson's Ratio	0.2	0.28	0.43	0.278
Fibre Volume Fraction (%)	60	60		60
Density (g/cm^3)	1.9	1.6	0.930	1.34

Common materials used in prosthetic sockets and proposed material (lyocell/EcoPoxy)The properties of lyocell are based on a study [18] which found that when lyocell fibre has a diameter between 150nm to 180nm the elastic modulus increases (98±6 GPa) much compared to one's greater than a diameter 180nm. Also, the EcoPoxy transverse elastic modulus is based on the moduli of Epoxy, as data of EcoPoxy is not readily available

Following these calculations, the effect of the braid angle on the properties of the lyocell- epoxy composite was calculated using the following equations:

Equations to Determine the Effect of Braid Angle on the Properties of lyocell/EcoPoxy

$S_{11}= 1/E_{11}$ $S_{22}= 1/E_{22}$ $S_{12}= -v_{12}/E_{11}$ $S_{66}= 1/G_{12}$

$$S\_L= (S_{11}(\cos(\theta)^4))+((2(S_{12})+S_{66})(\sin(\theta))^2(\cos(\theta))^2+(S_{22}(\sin(\theta)^4))$$

$$S\_T= (S_{11}(\sin(\theta)^4))+((2(S_{12})+S_{66})(\cos(\theta))^2(\sin(\theta))^2+(S_{22}(\cos(\theta)^4))$$

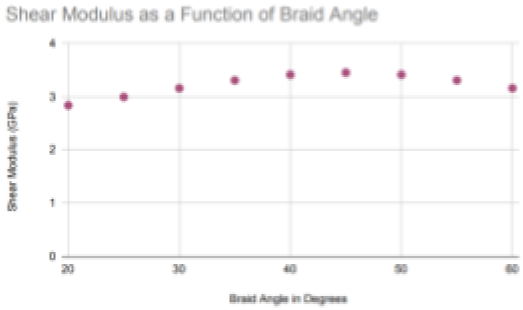
$$S\_G= (2(2S_{11}))+(2(S_{11}))-(4(S_{12}))-S_{66})(\sin(\theta))^2(\cos(\theta))^2+(S_{66}(\sin(\theta)^4)+(\cos(\theta)^4)$$

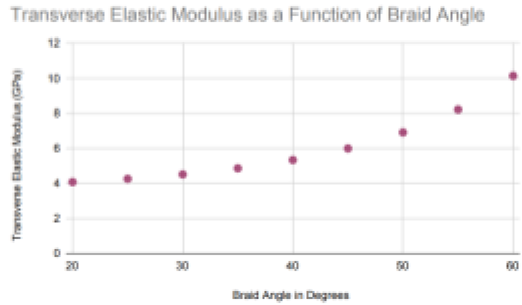
$E\_L=1/S\_L$ $E\_T=1/S\_T$ $G=1/S\_G$

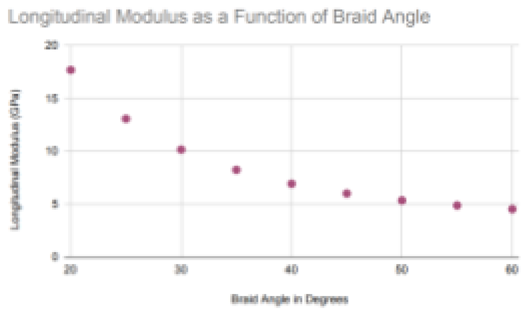
E_{11}= longitudinal elastic modulus of composite E_{22}= transverse elastic modulus of composite
G_{12}= shear elastic modulus of composite v_{12}= Poisson's ratio of composite
E_L= longitudinal elastic modulus of braided composite E_T= transverse elastic modulus of braided composite
G= shear modulus of braided composite
Figure. 3

Based on these calculations the new properties of braided lyocell/EcoPoxy was able to be discovered [19]

Resulting in the following graphs:







These graphs show that by increasing the braid angle both transverse elastic modulus and shear modulus increase, while the longitudinal elastic modulus will decrease.

Discussion The below model is an estimated model of the prosthetic socket:

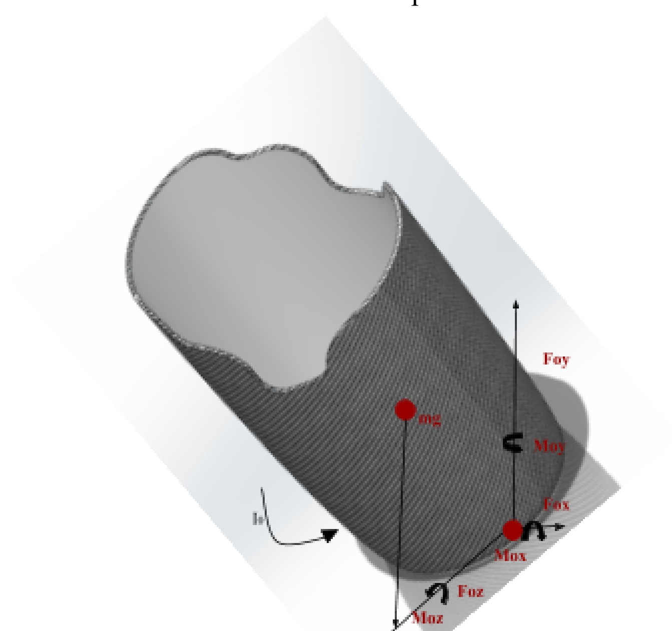


Figure 4

This model shows the need for a braided composite, as the prosthetic user experiences forces [20] and inertia both transversely and longitudinally

This model gives an estimate of the design of a lyocell-Ecopoxy braided composite prosthetic socket. It indicates the components one must consider when designing the prosthetic socket and the ability of lyocell-Ecopoxy to overcome such components.

Based on the characteristics of lyocell-EcoPoxy braided composite has the potential to be used as a material for a prosthetic socket, when considering lyocell with a diameter ranging from 150nm to 180nm, however, despite this carbon-fibre and glass-fibre are still more favourable than lyocell-EcoPoxy. When compared to polypropylene, lyocell-Ecopoxy surpasses its mechanical properties as it allows for environmental benefits while providing superior mechanical properties, although polypropylene does have a lower density. A lower density allows the amputee more comfort, as it allows for a low weight socket. Carbon-fibre provides a great advantage as it has high stiffness, high tensile strength, low weight to strength ratio, high chemical resistance, high temperatures tolerance, and low thermal expansion, such properties allow for a favourable prosthetic socket [21]. Glass fibre is quite economical, durable, flexible, and easily saturable with resin [22]. Despite the benefits of glass fibre composite and carbon fibre composite provide, lyocell is renewable, biodegradable, but also has higher purity, uniformity, and reproducibility of properties [23]. As well the light density of lyocell-EcoPoxy allows for competitiveness to be gained over other composites.

One issue that arises is the low shear strength of regenerated cellulose fibres such as lyocell. However, this was overcome by adding a suitable polymer matrix [24] and by braiding the material at a desirable fibre orientation angle, subsequently increasing the shear modulus. With a braid angle of 20° the shear modulus increases, from 2.52GPa to 2.836GPa, however, this cuts down the longitudinal elastic modulus from 59.932GPa to 17.652GPa. These values are still competitive with polypropylene. Also important to consider is the low density of lyocell-EcoPoxy which values are around 1.34g/cm^3 making it possible to create a low weight socket, for greater comfort and wearability for the prosthetic user. The shear modulus is important to consider, as it allows decreased discomfort from rotational inertia [25].

When examining other studies the use of plant fibres in prosthetic sockets shows that it would result in a lighter weight, cost-effectiveness, sustainability and more widespread availability, something critical for biomedical devices. However, it has also been found that when considering plant-based materials, such as Kenaf fibres, properties are based much on the arrangement and direction of fibres, fibre length, and composition [26]. This is why regenerated cellulose fibre, such as lyocell tends to allow for a more stable form of plant fibre subsequently allowing for consistency, despite sacrificing mechanical properties [27]. This proves another advantage of lyocell-Ecopoxy.

Conclusion The environmental, mechanical, and economic benefits of lyocell-EcoPoxy braided composite have a great potential to be used in the creation of prosthetic sockets. When considering a braid angle of 20°, the most favourable properties are available for use in a prosthetic socket as it gives the closest resemblance to the properties of glass fibre or carbon epoxy. The low density of lyocell-EcoPoxy also adds to the favourable properties. When comparing lyocell-EcoPoxy to polypropylene, a plastic also used in prosthetic socket production, lyocell-EcoPoxy is favourable when looking at environmental impact, mechanical properties, despite having a larger density. Furthermore, the properties of lyocell allow for high uniformity, something not prominent in natural fibres. Due to limitations of this study, Lyocell-EcoPoxy braided composites have not been lab-tested; therefore, future research should examine the ability of this material to provide an environmentally friendly alternative to be used in prosthetic socket design.

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