Artificial nature: possibilities for mycelial composite material design

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Abstract
Although the trend of interdisciplinary and non-disciplinary boundaries is becoming increasingly vigorous, due to the lack of knowledge related to biomaterials, in the process of using them for design practice, designers have developed a knowledge gap between design and material disciplines. Thus, they cannot integrate biological materials into product innovation to form artificial natural objects that are more ecological and life-like. This paper experimentally explores the way mycelium composites are used in product design in an attempt to incorporate the unique growth and rich sensory experience of mycelium materials into the design process. A design method oriented to biomaterial innovation is proposed, and a prosthetic protective cover is designed using this method. By developing agricultural waste into biological mycelium materials, products are re-endowed with a time-sense compound experience and a rich sensory experience, thereby creating artificial natural objects with the ability to repair nature.

Author keywords
Mycelial materials; Material experience; Biomaterial design; Artificial nature.

Introduction
Materials, as an important innovative element in design activities, unsustainable materials, and their product applications are constantly pressing the limits of Earth's ecosystem. Biomaterial design, as a typical interdisciplinary discipline, presents strong potential for innovation, mainly in that biomaterials provide a variety of alternative production methods, such as biomanufacturing and natural growth, for current production activities. For example, the representative mycelium composite material in biomaterials, with the help of the automatic force of fungal growth, helps designers change the traditional role of passive application of material properties; however, forward thinking utilizes the properties of biomaterials and introduces them into design activities throughout the entire process.

This paper will use mycelium composite material as an example of a prosthetic protective cover material and employ methods such as material experiments and the innovative design of biological materials to study the objective and subjective characteristics of mycelium materials. Through the new design method and experiment, this research has preliminarily obtained a new experience quality for the material. Due to its non-toxic and harmless natural growth method, it can not only replace the traditional industrial production method but also reduce its incidental pollution problems. The above results will provide theoretical and practical references for the design of emerging materials and their application areas in the future. A design approach based on material innovation will simultaneously change the designer's role of passively selecting materials to one of actively and experimentally creating new materials and promoting the rapid application of new materials in design activities.

Research on the Characteristics of Mycelium Composite Materials
Mycelium is the vegetative part of fungi, such as Ganoderma and mushrooms, and it is also called "the root of mushrooms." Mycelium is composed of many microscopic mycelial long-line fiber structures that use the enzymes secreted by themselves to decompose the polymers in the matrix and produce the nutrients needed for growth (Appels et al., 2019). In addition, mycelium functions as a "natural glue" that penetrates the gaps of the matrix material by the growth of mycelium and eventually forms interlocking structures to produce biocomposites (Elsacker et al., 2020). Combining the objectives and experimental materials of this research, the author will focus on the design method and application research of mycelial composites to reveal the potential future application and development value of the material through an experimental exploration of the subjective and objective design characteristics of mycelial composites.

Subjective properties of mycelium composite materials
Humans carry the environmental influences of society and culture to perceive the unique qualities of materials through the five sensory organs of the body. The subjective properties of materials are the characteristics with which humans form perceptions with the help of multiple senses, such as touch, which contains emotions, a sense of experience, etc. (Sun, 2016). It is often more akin to a sensory interaction between

materials and people that occurs through the human sensory organs to perceive and stimulate psychological and physiological response attributes (Zuo, 2010). This research will focus on mycelium composites, which have a flowing "time" quality and material texture due to their unique biological properties. To obtain people's subjective characteristic evaluations of new biomaterials, the author used a focus group method to collect qualitative data on the subjective characteristics of mycelium materials and summarized them in a table. A table of the subjective characteristics of the mycelium composite material was established (Table 1).

Table 1. Sensory properties of mycelium composite materials.

Sensory	Properties
Tactility	Sometimes delicate and sometimes rough; the delicate part is like soft skin
Texture	Bumpy natural fiber texture with some irregular signs of use
Color	Scattered pale yellow small spots among large areas of white
Form	Non-fixed organic looking form, twisted and squeezed into a shape at will
Odor	Has a special natural odor; the smell is reminiscent of a haystack after rain

By experiencing the quality of materials first-hand, designers and users avoid being limited to capturing the objective characteristics of materials, thereby ignoring the relationship between new materials and external factors (Yin, 2017). According to the table of the subjective properties of the material, this biomaterial, characterized by growth and dynamics, develops an imperfect experience of the passage of time.

Objective properties of mycelium composite materials

Through queries and combing literature related to the properties of mycelium materials, the three dimensions of material composition, physical properties, and chemical properties were explained in detail.

1. Composition of mycelial composites. Mycelium grows by sticking to the substrate matrix to form biocomposites. Different types of fungus seeds and substrates ultimately affect the properties and growth conditions of the material. At present, it is common to inoculate substrates with species of Basidiomycota, which have two important characteristics: septum and anastomosis (Alemu et al., 2022). In the selection of substrate materials, agricultural waste, such as straw, sawdust, wheat bran, corn cobs, straw, fallen leaves, etc., can be used, as well as tea leaves, fruit and vegetable peels, coffee grounds, nut shells, etc. that are discarded in daily life, giving the material the ability to degrade quickly and naturally.
2. Physical properties of mycelial composite materials. After the mycelium material has finished growing, it presents an open porous structure similar to sponges and bones. The combination of the three-dimensional structure and chitin in fungal cells makes the material extremely light yet strong (Haneef et al., 2017). This unique porous structure enables it to absorb sound waves in the frequency range of 350 Hz to 4 kHz (Pelletier et al., 2019). It is a potential sound-absorbing and sound-insulating material. A related study tested the physical and mechanical properties of two groups of mycelial materials with different substrates made of wood, sawdust, and a combination of sugarcane and cassava roots. The final results of the tests showed that the density of the first group of materials reached 420 (kg/m^3), while the density of the second group of materials was 440 (kg/m^3); the average modulus of elasticity was 3.97 (MPa) for the first group of materials and 22.7 (MPa) for the second group; and the average compressive stress at 5% deformation was 0.17 (MPa) for the first group of materials and 0.61 (MPa) for the second group of materials (Heisel et al., 2017). Clearly, different combinations of substrates and their processing methods affect the density and tensile and compressive strength of mycelial materials.
3. Chemical characterization of mycelial composite materials. Fire resistance and non-allergenicity are two chemical properties that mycelium materials possess. In terms of fire resistance, chitin produced by fungi is a natural polymer whose combustion requires high heat (Silverman et al., 2020). The substrate covered by the growth of chitin in the hyphae has high fire resistance properties; thus, this material is also called a natural fire retardant. Its non-allergenic nature is due to the substrate it uses being a natural and environmentally friendly material. The mycelium forms a soft white covering after it finishes growing on the substrate. Finally, the material is sterilized at high temperatures for up to several hours to effectively remove bacteria and other microorganisms.

Application of Mycelium Composite Material in the Design of a Prosthetic Protective Cover

Creating product goals

This paper takes the material-driven design method (MDD) proposed by Karana as the basic process (Karana et al., 2015) and fine-tunes it with the application scope of mycelial composites and prosthetic protectors cover. Eight steps of the biomaterial design approach are proposed. Design a protective cover product for the disabled that provides calf prosthetic protection and decoration functions and constructs an innovative design process for mycelium composite materials. The prosthetic protective cover can provide a collision protection function for prosthetic parts and realize beautification and waterproof functions by covering the prosthetic parts. Studies on users with physical disabilities have shown that people with disabilities not only need tools to assist them physiologically but also have a strong sense of inferiority and rejection psychologically. The addition of mycelium materials can reconstruct the visual, tactile, and other multisensory interaction modes of rehabilitation aids (Zhao et al., 2020), bringing more emotional care to the disabled.

Material property matchingj

Based on the analysis of objective and subjective characteristics of mycelium material above, match the material characteristics with the product objectives. Query whether the material characteristics can meet the user requirements and product development objectives. This design successfully

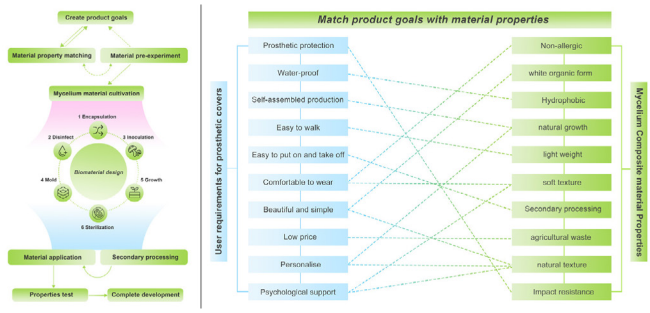

Figure 1. Left: Mycelium composite material design flow chart ; right: Matching of product requirements and material properties.

Figure 2. Left: Mycelium protective cover cultivation process: (a) substrate disinfecting; (b) inoculation; (c) adding material into the mold; (d) mycelium grows naturally; (e) drying material ; right: mycelium prosthesis protection cover wearing effects.

matches the user requirements and material properties (Figure 1), the prosthetic cover will be designed in depth.

Mycelium material pre-experiment and cultivation

After comparing the color, odor, form, touch, and texture between the six mycelium material samples and the impact resistance test, the sample with the material formulation of Ganoderma, wood chips, wheat bran, and glucose was selected because the subjective and objective characteristics of this sample met the product development needs.

To begin, the chopped sawdust and wheat bran were mixed according to 70% and 30% of the total mass of the material, respectively, placed into a sealed bag, and sterilized in a high-temperature environment of 100 °C for 2 hours to prevent the substrate from being contaminated by bacteria. After the inoculation was completed, the substrate was placed in a sealed bag with a breathing valve, and the mycelium was left to colonize and grow in the substrate for one week. The colonized mycelium composite material was then placed into the mold, and pressure was applied to limit the growth space of the material and to generate the shape to be molded. After eight days of growth in the mold, the shaped mycelium composite was removed. It was placed into a sealed bag and grown again for seven days, allowing the mycelium to completely cover the substrate and increasing the strength and density of the material. During the cultivation process, the mycelium growth environment temperature should be controlled at 25°C–30°C, and the relative humidity should be 80%–90%. Finally, after growth, the mycelium composite material was placed into an oven and baked under convection at 100 °C for 2 hours to remove the fungal activity and moisture in the mycelium. The mycelium protective cover cultivation process is shown in.

Secondary processing and material application

To realize the convenience of wearing the prosthetic protective cover, secondary processing is required. To date, a calf prosthetic cover based on mycelium biomaterial has been fabricated. The steps for wearing the mycelium prosthetic cover are shown in, and the effects are shown in (Figure 2).

Material properties test

A material testing machine was used to test the mechanical properties of the prosthetic material The mechanical properties of the complete mycelium prosthetic cover were tested. The test was divided into a vertical cross-section and a transverse cross-section of the protective cover, test process, and results (Figures 3). A series of material performance tests proved that the performance of mycelium material is between that of rigid polymer foam and polyethylene, and the prosthetic protective cover made of mycelium material can provide corresponding protection functions and meet its basic performance requirements.

As an emerging biological material, mycelium's biophilic properties can help designers create a more ecological and natural artificial nature and integrate it with nature to form a "living" artificial natural object. Designers also have the opportunity to be the subject of life-shaping, blurring the boundaries between living and non-living, and presenting a cooper-

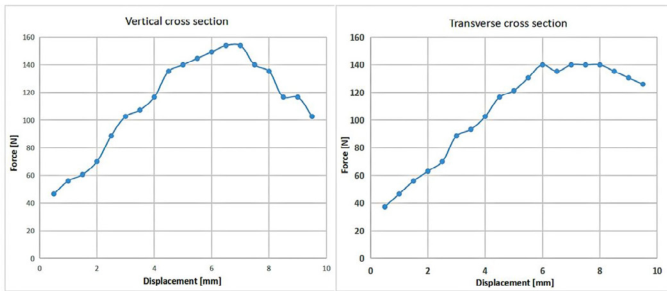

Figure 3. Left: maximum compressive force of vertical cross-section; right: maximum compressive force of transverse cross-section.

ative model of mutual integration and symbiosis between human and non-human species. Based on the exploration of the implicit and explicit characteristics of mycelium materials, this study provides designers with a biomaterial-driven innovative design approach through the experimental application of biomaterials in the design of rehabilitation assistive devices. It is worth noting that the physical properties of the material will be affected by product function, manufacturing technology, and the use environment. Therefore, designers need to further investigate the application of the material in diverse products, in addition to testing the mycelial prosthetic cover through international standards to verify the usability of the product. The innovative application of biomaterials expands designers' imaginations and gives products a new sensory experience. In addition, mycelium materials use new biomanufacturing models to naturally "grow" carbon-negative products with low energy consumption, and they can be combined with different agricultural wastes to produce unique material textures to meet the individual needs of users. The experimental application research of mycelium material also builds many possibilities for the future application development of biomaterials in design and can even rebuild the artificial new order of nature with the help of its biological elements.

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