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A Review of Lightweight Research on 3D Printed Prosthetic Structure Based on Topology Optimization

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Abstract: The lightweight of prosthetic limb is the key to improve the wearing comfort and user experience. The integration of topology optimization and 3D printing technology provides a new path for it. This paper reviews the application status, key technologies and existing problems of topology optimization and 3D printing in the field of lightweight prosthetic limbs. The research shows that the integration of topology optimization and 3D printing is an important direction for the lightweight and customization of prostheses. At present, there is still room for improvement in algorithm adaptation and process coordination. In the future, it is necessary to promote the landing of technology through multidisciplinary cross-disciplinary to provide better rehabilitation aids for the disabled.

Keywords: Topology Optimization; 3D Printing; Prosthetic Limbs; Lightweight Structure

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1. Introduction

With the increasing demand for rehabilitation of disabled people and the acceleration of population aging, prosthetic limbs have attracted attention as core rehabilitation aids. Although breakthroughs have been made in related research, there are still many bottlenecks in traditional prostheses: solid structure design leads to large weight and discomfort in wearing, traditional manufacturing processes are difficult to achieve complex lightweight structures, and personalized customization has a long cycle and high cost, which cannot meet the user's ergonomic and biomechanical needs.

As an advanced structural optimization design method, topology optimization technology realizes the optimal distribution of structural materials through algorithm iteration under given load and constraint conditions, and can remove redundant materials to the maximum extent without reducing mechanical properties[1, 2]. 3D printing technology breaks through the limitations of traditional subtractive manufacturing. It has the advantages of high customization, fast forming speed and strong manufacturability of complex structures. It can accurately reproduce the complex lightweight structure of topology optimization design and solve the limitations of traditional manufacturing process[2-4]. The e-NABLE project launched in 2011 is one of the pioneers of 3D printing low-cost children's prostheses, which proves that functional instruments can be produced at a small cost of traditional prostheses, leading to the popularity of customized robot prostheses[2, 5]. The deep integration of topology optimization technology and 3D printing technology has become an effective way to solve the lightweight and customized pain points of traditional prostheses.

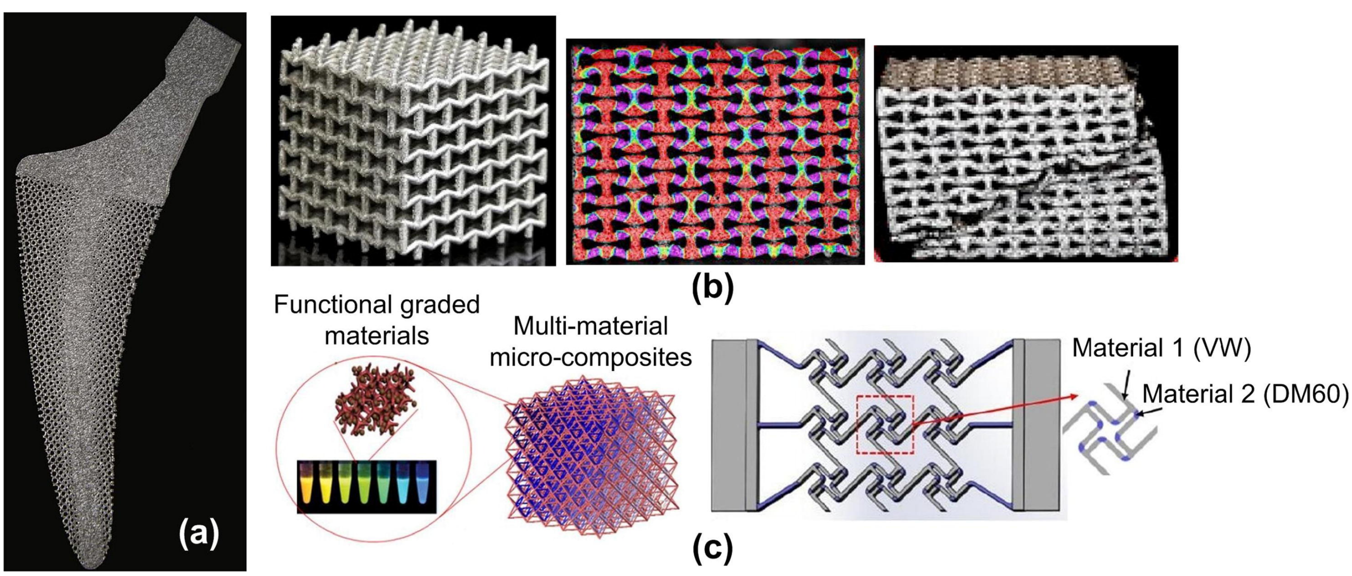
Focusing on the core line of topology optimization-3D printing-lightweight prostheses, this paper systematically reviews the research status in this field, summarizes the key technologies, research results and existing deficiencies in the current research, in order to promote the deep application of topology optimization and 3D printing technology in the field of lightweight prostheses.

2. Topology Optimization of Lightweight Prosthetic Structure

2.1 Principle and Method of Topology Optimization Technology

Topology optimization is an advanced design method based on structural mechanics and mathematical optimization theory. Its core objective is to determine the optimal distribution of materials through optimization algorithm iteration under given design space, load conditions and performance constraints, so as to achieve the balance between "lightest weight" and "optimal performance". Compared with size optimization and shape optimization, topology optimization does not need to presuppose structural form, can independently generate the optimal structural layout, and is more likely to break through the limitations of traditional design thinking. It is especially suitable for complex structural design such as prostheses that need to take into account both mechanical properties and lightweight. Vogiatzis et al.[6] used the level set method to optimize the topology of single-material and multi-material negative Poisson 's ratio microcomposites. Based on isogeometric analysis, Gao et al.[7] realized isogeometric topology optimization to obtain negative Poisson's ratio microcomposites. Zhang et al.[8] combined the density-based topology optimization method with the mixed stress/deformation-driven nonlinear homogenization method to design microcomposites with negative Poisson's ratio behavior in a large strain range. In addition, as shown in Figure 1, functional micro-composites with maximum effective bulk modulus (EBM) have received extensive attention and are widely used in load-bearing structures[2, 9, 10].

Figure 1: (a) Microstructures in biomaterials applications[2], (b) Functional microstructures during deformation and failure[10], and (c) Multi-material microcomposites[10]



At present, the topology optimization methods for lightweight design mainly include density method[11], level set method[12], genetic algorithm[13], etc., as shown in Table 1. The variable density method has become the most commonly used optimization method in related research because of its simple principle and high computational efficiency. The level set method and genetic algorithm play an important role in the surface accuracy control of the prosthetic limb and multi-objective optimization respectively.

Table 1: Topology optimization method

Typical Topology Optimization Methods	Advantages	Disadvantages
Density Method	Simple principle, high computational efficiency, easy to implement, and wide application	Low boundary precision, requiring subsequent smoothing treatment
Level Set Method	Precise boundary control, suitable for high-precision requirements	Complex calculation, low efficiency, and application in the exploration stage
Genetic Algorithm	Strong global search ability, capable of handling multi-objective optimization	Low computational efficiency, many iterations, affecting the design cycle

2.2 Topology Optimization Constraints of Lightweight Prosthetic Structure

As a rehabilitation assistive device in direct contact with the human body, the topology optimization design of the prosthetic limb needs to take into account multiple constraints such as mechanical properties, ergonomics, and biocompatibility. Mechanical performance constraint is the core. It is necessary to ensure that the prosthetic limb has sufficient strength, stiffness and stability under static load and dynamic load, so as to avoid fracture and deformation during use. Ergonomics constraints require the optimized prosthetic structure to fit the shape of the human body, with accurate size and comfortable wearing, so as to avoid local compression, friction and other problems[14]. Biocompatibility constraints require the topology optimization process to combine the characteristics of 3D printing materials to ensure that the optimized structure is compatible with the printing material[15]. RASZEWSKI et al.[15] have shown that it aims to prepare a bioactive 3D printing material that can be used in transparent removable orthodontic appliances. By adding bioactive glass to the acrylic monomer, the performance and cytotoxicity tests show that the material has stable ion release, good mechanical properties and good cell compatibility, and can be used for orthodontic appliances.

In addition, the topology optimization of the prosthesis also needs to consider the manufacturing constraints, that is, the optimized structure needs to meet the requirements of the 3D printing process, avoid the complex structure that cannot be formed (excessive small support structure, closed cavity, etc.), and ensure that the lightweight structure can be accurately realized by 3D printing. The coupling of multiple constraints makes the topology optimization design of prostheses more complex and challenging, and has become the focus and difficulty of current research.

3. Lightweight Design of 3D Printed Prostheses Based on Topology Optimization

At present, the integration of topology optimization and 3D printing technology has become the core path of lightweight and personalized design of prosthetic structure, forming a series of research results, but also showing different research focuses and common problems.

3.1 Lightweight Structure Design and Optimization Method

In the application of lightweight structure design and optimization methods, researchers have focused on combining the biomechanical properties of prosthetic limbs with ergonomic requirements to explore the adaptive application of topology optimization technology. Generico Chair, designed by Marco Hemmerlin et al.[16], applies the topology optimization idea system to the chair structure design. By optimizing the material distribution, the weight is significantly reduced while ensuring the mechanical reliability. Current research has explored new biomaterials such as shape memory polymers and piezoelectric composites, which are expected to achieve adaptive stiffness adjustment and embedded sensing functions of the next generation of prostheses. By matching material properties with functional requirements such as quality reduction, energy feedback, and interface comfort, the designer successfully developed a prosthetic foot structure that combines performance optimization and patient experience improvement. Figure 2 shows a prototype device based on representative materials[17].

Figure 2: 3D printed prosthesis example[17]: (a) polylactic acid (PLA), (b) titanium alloy lattice structure, (c) CFRP, (d) composite

3.2 Personalized Customization and 3D Printing Process

In terms of personalized customization and process adaptation, relying on the customization advantages of 3D printing, combined with topology optimization to achieve precise design and efficient manufacturing of prostheses. Figure 3 is the flow chart of the production of prosthetic limbs using 3D printing technology. Based on biomechanics and 3D printing technology, researchers collected three-dimensional data of human limbs, established personalized biomechanical models, and combined topology optimization with selective laser sintering (SLS), fused deposition modeling (FDM) and other processes (Figure 4) to create lightweight prostheses that meet individual needs[17]. Some studies focused on process improvement and cost control, and formed targeted results : researchers carried out ankle prosthesis design, combined with topology optimization to optimize joint structure, and improved the activity performance and lightweight level of prostheses[18]. Another study, from the perspective of embodiment, combined with topology optimization and selective laser sintering process, designed a child prosthesis that takes into account both lightweight and comfort, and solves the pain points of children's prosthetic limbs with high personalized needs and fast growth and development[19]; 3D technology provides new opportunities for imitating and manufacturing multi-scale, multi-material and multi-functional structures in nature, and provides high-quality material support for topologically optimized prosthetic structures, further improving lightweight effect and biocompatibility[20].

Figure 3: The process of using 3D printing technology to manufacture prosthetic limbs[21]

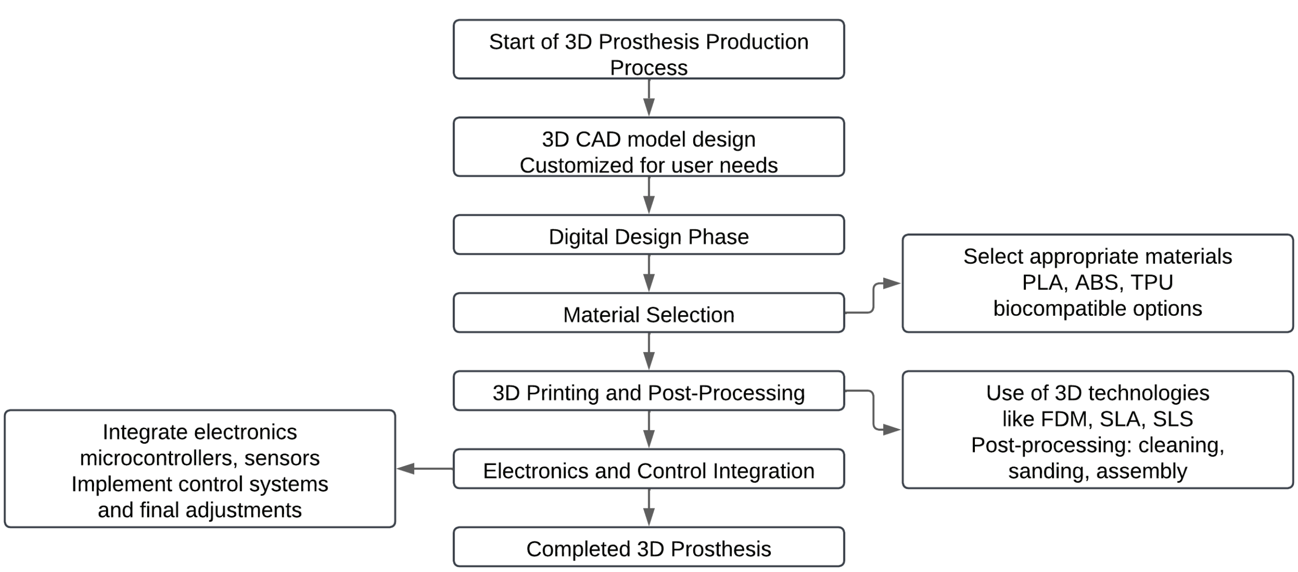
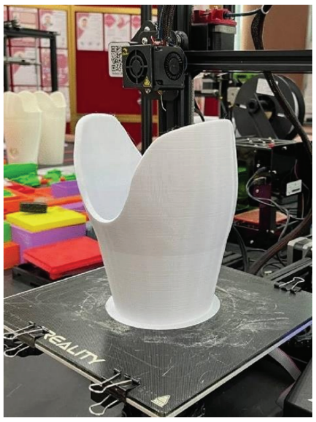


Fig. 4 Representative additive manufacturing cases[17]: (a) FDM printed prosthesis socket; (b) Prosthetic sockets were made by SLS



a

b

4. Key Technologies and Research Hotspots

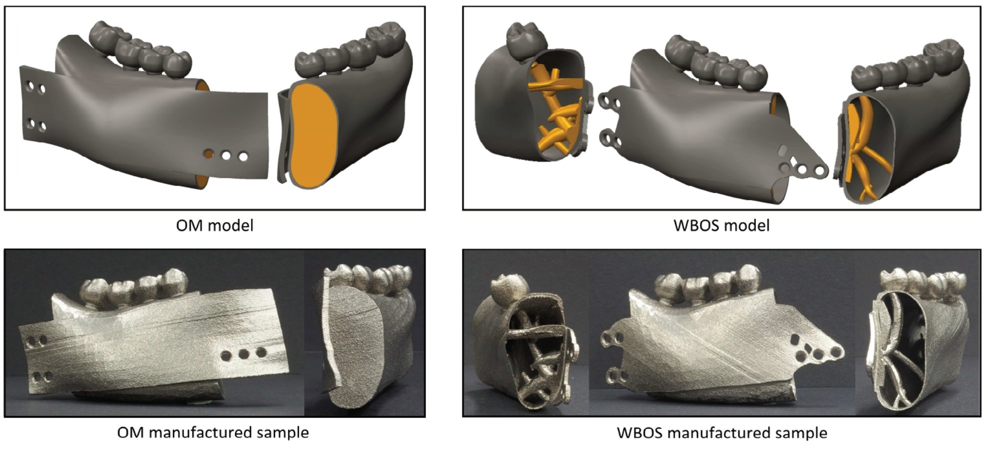
4.1 Multi-objective Collaborative Design of Prosthetic Topology Optimization

At present, the topology optimization of lightweight prosthetic structure has shifted from a single weight optimization to a multi-objective optimization of "lightweight+mechanical properties+ comfort+manufacturing feasibility", which has become a research hotspot. The core of multi-objective collaborative design is to establish a reasonable optimization objective function and balance the contradiction between the constraints. For example, the balance between lightweight and mechanical properties, the balance between individual adaptation and manufacturing feasibility[22, 23]. The researchers solved the conflict problem in multi-objective optimization by introducing weighting coefficient method, Pareto optimal solution and other methods to ensure that the optimized prostheses not only meet the lightweight requirements, but also have good mechanical properties and wearing comfort.

4.2 Synergy of Topology Optimization and 3D Printing Process

The collaborative adaptation of topology optimization and 3D printing process is the key to realize the lightweight design of prosthetic limbs. On the one hand, it is necessary to adjust the constraints of topology optimization according to the characteristics of 3D printing process[24, 25], so as to avoid designing complex structures that cannot be formed. As shown in Figure 5, Li et al.[24] used a weighted topology optimization method to design a specific intimal implant for patients with severe inferior membrane defects, providing good biomechanical properties and appearance repair for oral rehabilitation. On the other hand, it is necessary to improve the forming quality of the topologically optimized structure by optimizing the 3D printing process parameters to ensure that the formed prosthetic structure is consistent with the optimized design. At present, the commonly used collaborative adaptation methods include topology optimization design under process constraints, matching test of printing parameters and optimized structure, etc., which has become the focus of current research.

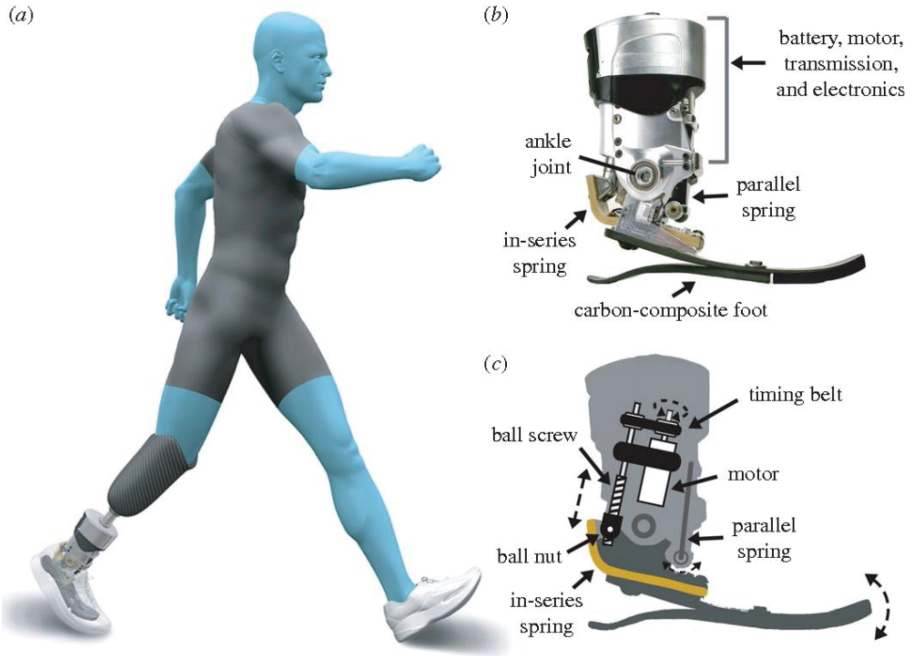
Figure 5: The model before and after the final optimization, and the corresponding physical model was made by metal 3D printing technology[24]



4.3 Topology Optimization Based on Biomechanics

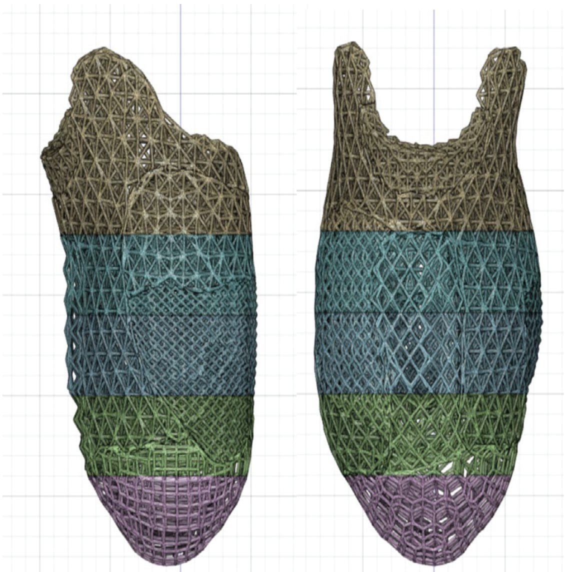
The performance of prostheses is closely related to the biomechanical properties of human body. Personalized topology optimization based on human biomechanical data is the core technology to improve the adaptability of prostheses. Researchers collect multi-dimensional biomechanical information of users, construct personalized models and integrate them into the whole process of topology optimization, so that the prosthetic structure is more suitable for human body shape and exercise habits, and significantly improves wearing comfort and exercise flexibility. Through the wear test of tibial amputees, the fitness, comfort and stability of the prostheses were improved, which confirmed the clinical applicability of the optimized design[26]. The synergistic effect of the comprehensive verification method ensures that the 3D printing topology-optimized prosthetic foot meets the requirements of performance, durability and user experience (Figure 6).

Figure 6: Assessment of fitness and gait by transtibial amputee test[17]



In addition, combined with finite element simulation technology, the mechanical response of prostheses under different motion conditions can be simulated, and the structural design can be further optimized to ensure the reliability and safety of prostheses. In the topology optimization study of the prosthetic socket (Figure 7), different lattice structures are proposed to simulate the stiffness of different regions of the flexible socket[27].

Figure 7: Different lattice structures are used to simulate the stiffness of different regions of the flexible receiving cavity[27]



5. Development Trends

At present, there are many deficiencies in the lightweight research of 3D printed prosthetic structure based on topology optimization, and the future development needs to be targeted.

• Innovate a dedicated optimization algorithm to improve the adaptability and computational efficiency of the algorithm to the design of prosthetic limbs.

• Promote the deep coordination of topology optimization and 3D printing process, optimize printing materials and process parameters, and solve the problem of structural forming.

• Strengthen clinical verification and industry-university-research cooperation, promote the implementation of technical engineering, reduce manufacturing costs, and achieve large-scale production.

Conclusion

The collaborative integration of topology optimization and 3D printing technology effectively breaks through the bottleneck of traditional prosthetic design and manufacturing, and constructs a new technical system for lightweight and personalized design and manufacturing of prosthetic limbs, which significantly improves the mechanical properties, wearing comfort and customization level of prosthetic limbs. This paper reviews the research results in this field, clarifies the key technologies such as the core method of topology optimization, multi-constraint design and process collaboration, and summarizes the existing problems in algorithm adaptation, process collaboration and clinical verification. In the future, we need to focus on the direction of personalized and engineering development, promote the large-scale implementation of technology through technological innovation and industry-university-research collaboration, realize the high-quality development of prosthetic rehabilitation aids, and provide rehabilitation support that is more suitable for the needs of the disabled.

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Conflict of Interests

The authors declare that there is no conflict of interest regarding the publication of this paper.

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