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Personalized Prosthetic Design Based on Artificial Intelligence and 3D Printing Technology

Zihang Ma[1,*]

[1]Department of Zheng Zhou NO.9 high school, Zhengzhou, China
*Corresponding author: mark027829@gmail.com

Abstract:
The integration of artificial intelligence (AI) and 3D printing technologies is transforming the field of personalized prosthetic design. It offers solutions that meet the specific needs of different patients. Traditional prosthetics have problems such as long manufacturing cycles, high prices, and inability to meet the specific needs of a small number of patients. However, if AI technology is combined with 3D printing technology, each patient can be given a unique diagnosis, and a personalized diagnosis can be provided. The service of providing customized prosthetic limbs for each patient. Prosthetics play a significant role in restoring the mobility of disabled individuals and improving their quality of life. However, traditional prostheses have limitations, such as long manufacturing cycles (The period of a normal prosthetic limb picking date is about 4 to 8 weeks), high prices (This results in the poor being unable to use prosthetic limbs), and inability to meet the special requirements of specific groups of people. For example, children and athletes often have different prosthetic needs than the general population. Artificial intelligence (AI) is the capability of computational systems to perform tasks typically associated with human intelligence. Combining artificial intelligence technology with 3D printing provides solutions to the challenges faced by ordinary prosthetics.

Keywords: Artificial intelligence; 3D printing; Personalized prosthetics; Medical devices.

1. Introduction

According to the World Health Organization [1], over 57 million people worldwide have lost limbs due to trauma, disease (such as diabetes-related amputations), or congenital defects. Prosthetic limbs are more than just assistive devices; they are crucial for achieving independence: they help users complete daily activities like feeding and dressing themselves and reintegrate into society.

1.1 The Challenges of Traditional Prosthetic Manufacturing

The production process of traditional prosthetics is complicated and is made by hand. Usually, people first use plaster or foam to make a model of the prosthesis, and then use metal or composite materials to make the prosthesis. During the manufacturing process, it needs to be polished and adjusted many times to meet the needs of the patient. For example, varies greatly depending on prosthesis type; it can take between one week and several months. Prosthetic limbs are also usually expensive to manufacture, making them very expensive. As a broad range, lower-extremity prosthetic legs can cost between USD 3,000 to USD 24,000 depending on the type of device [2]. This leads to the high cost and time cost of traditional prosthetics.

Despite the complex manufacturing process and high manufacturing costs of traditional prostheses, they are produced based on standard sizes and cannot meet the different needs of each patient's different physical conditions (special muscle distribution, residual limb shape, etc.). For example, about child patients Since children are still growing, prosthetic devices need to be replaced or resized every 12–18 months, creating a much higher cumulative financial burden compared to adults. [3] Because traditional prosthetic limbs are expensive and require frequent replacement, many families cannot afford prosthetic limbs for their children.

2. Theoretical Research

2.1 An Integrated Solution: AI and 3D Printing

In the past decade, breakthroughs in AI and 3D printing have provided new ideas for solving these problems. People have combined the two technologies to create new prosthetic limbs. AI technology plays an important role in the personalized setting of prosthetic limbs. AI-driven modeling optimizes prosthetic fit, suspension systems, and biomechanics, cutting down adjustment sessions and long-term expenses, and machine learning enables automated gait analysis, improving performance and reducing costly trial-and-error fittings.

Although AI and 3D technology have their own advantages in the field of prosthetic manufacturing, they both have limitations. AI can quickly analyze patient data and design prosthetic limbs that are suitable for the patient, but it cannot quickly manufacture prosthetic limbs. 3D printing can quickly manufacture prosthetic parts, but it relies on pre-designed drawings. If you want to combine artificial intelligence and prosthetic limbs, the most important thing is to combine AI's data analysis and design capabilities with 3D printing's rapid manufacturing capabilities. Using this technology to solve the challenges faced by traditional prosthetics (long manufacturing cycle, high manufacturing cost, inability to meet patient personalization, etc.)

2.2 Data Acquisition: The Foundation of Personalization

The production and manufacturing process of a qualified prosthesis can be roughly divided into some parts: the collection and analysis of the patient's physical data, the design of a prosthesis suitable for the patient using AI technology, and the selection of suitable materials and the use of 3D printing technology to manufacture the prosthesis.

2.3 Collection and analysis of Patient Physical Data

Collect detailed physical data of patients through various sensors, such as 3D scanner, biological sensors and so on. Plaster casting has long been used to make prosthetic models because it does not require expensive manufacturing costs. However, it is highly dependent on the staff's skill in making the mold, which directly affects the time consumption, accuracy, and suitability of the mold for the patient. Repeated castings can experience volumetric inconsistencies as high as 5%-10%. In contrast, 3D scanning is a faster, contactless, and more comfortable process, providing highly repeatable results with a volumetric error of only approximately 1%-2%. Furthermore, digital data is easily stored, transferred, and integrated into CAD/CAM systems. However, its disadvantages include the need for specialized equipment with a higher initial cost, a learning curve for the software, and potential accuracy issues caused by reflective surfaces or patient movement during scanning. [4] The imaging, biomechanics, and physical measurements and them will be feed into digital models. AI helps interpret complex datasets, improving the accuracy of prosthesis fitting. Through AI's deep learning and artificial intelligence modeling, patients' specific needs can be predicted, the structure can be optimized, and repeated trials can be reduced, reducing the time cost and trial-and-error cost in the prosthetic design process.

2.4 User Demand Data Collection.

User needs ensure that the prosthesis matches lifestyle and personal preferences, which are mainly collected through the following methods.

Structured interviews: Focus on activity level (e.g., "Does the patient participate in sports?"), comfort priorities (e.g., "Which is more important, weight or durability?"), and

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aesthetic preferences (e.g., prosthetic color or printed designs).

Quality of life assessments: Standardized tools (e.g., the Prosthetic Evaluation Questionnaire (PEQ)) are used to measure indicators such as mobility and social integration, providing a basis for design trade-offs (e.g., designing more durable prostheses for outdoor workers) .

2.5 Data Processing and Feature Extraction

Then the raw data must be cleaned and standardized to ensure reliable use in AI-based prosthetic design. Noise reduction is essential to remove interference from 3D scans, such as clothing artifacts or motion-induced distortions, as well as from biosensor signals like EMG. Techniques such as Gaussian filters or Statistical Outlier Removal (SOR) are often used for 3D point clouds, while band-pass filtering is applied to EMG signals [5]. Feature extraction focuses on identifying key biomechanical characteristics, including residual limb geometry, joint range of motion, and pressure distribution. For instance, CNNs can automatically detect load-bearing regions from 3D scan data to improve socket design [6]. Finally, data fusion integrates multiple data sources, such as user activity data, gait patterns, and material properties, into a unified framework. This allows AI systems to match patient-specific needs with optimal prosthetic structures and materials, enabling highly personalized designs [7].

2.6 AI-Driven Design and Simulation

Taking advantage of AI's own learning function to create and simulate the possibility of prosthetic limbs. People input their individual needs and respective body information to AI, and AI, utilizing algorithms, determines the analysis of the body information and integrates it and individuals' special demands to create prosthetic limbs that fit individuals. When creating prosthetic limbs, AI utilizes some special algorithms. With these algorithms, it generates general designs based on preestablished rules in line with human physiology and engineering laws. For example, the finger length of an upper-limb prosthesis can be determined to around 70% of the respective finger length of the intact hand to have both function and natural looking [8]. Analogously, lower-limb prosthesis socket wall thickness tends to be kept between 3–5 mm to make a balance between strength and mass, and the respective value tends to be determined based on residual limb pressure information and material characteristics [9]. Furthermore, AI tends to automate joint alignment optimization in lower-limb prosthetics and shift the knee axis 5–10 mm to the posterior of the anatomical axis to enhance stabilitas when walking [10]. With these rule-based algorithms, safety, comfort, and ergonomics are ensured to be in line with the basic design of the prosthesis and provide a basement for AI-optimized further optimization.

For instance, a personalized lower-limb prosthesis for a high-speed runner can be generated with these rule-based algorithms. The AI initially interprets the runner's 3D scan and it's gait information, and it determines the socket wall thickness to be 4 mm to achieve a lightweight design versus bone strength balance [9]. It also configures the knee joint axis to shift 7 mm behind the anatomical axis to achieve enhanced stabilitiy when running at high speeds [10-13]. It further determines the prosthetic foot stiffness based on the runner's body weight and stride rate to deliver energy-effective performance. It shows how parametric rules AI-based can spit out a deployable baseline design that achieves both safety and performance needs prior to final customization.

2.7 Material Selection and 3D Printing Fabrication

Select the Appropriate Material and Proceed with 3D Printing. Since everyone's situation is unique, the materials used in producing prosthetic limbs also vary. For general patients, we typically use TPU (Thermoplastic Polyurethane) as the custom material. This material is favorable for shaping and is low-cost, making prostheses manufactured with it advantageous in terms of short production cycles and affordability.

Prosthetic limbs made from TPU can save 3–5 days in production time and reduce manufacturing costs by approximately 50% compared to traditional prosthetics. However, for certain special populations, other materials are required. For instance, individuals with obesity often demand higher strength from their prosthetic devices. In such cases, materials like fiberglass or carbon fiber, which offer greater strength, may be chosen to fabricate more durable and reliable prostheses.

In addition, lightweight, wear-resistant, and eco-friendly materials are typically chosen for children patients in order to fit their daily active routines and growth wakening. For sportsmen or extremely active users, high-performance engineering plastics and composite are usually advised in order to strike a perfect combination between strengths, flexibility, as well as resilience.

Once the material is determined, 3D printing technology enables the rapid and precise fabrication of prosthetic models. This technology not only supports a high degree of personalization to match the user's physiological structure but also allows quick design adjustments through iterative optimization, significantly improving fitting efficiency and user comfort. In the future, with continued advancements in material science and 3D printing, the production of personalized prostheses will become even more efficient, economical, and functionally diverse.

For instance, in the case of a young athlete requiring a high-performance below-knee prosthesis, traditional materials like thermoplastics (e.g., TPU) are often insufficient to withstand high-impact loads. Instead, a carbon fiber composite socket and footplate are typically employed for their superior strength-to-weight ratio and exceptional energy return, which are critical for dynamic activities like running and jumping [14]. Complementing this, the integration of additive manufacturing allows for the creation of custom-fit, functional components that further enhance performance. A notable example is the digital design and 3D printing of a lattice-structured liner from a durable polymer like Nylon (PA12). This bio-conforming lattice structure, that would otherwise be impractical to produce conventionally, greatly optimizes pressure distribution, minimizes shear stress, and regulates moisture, consequent to increasing overall comfort and stabilitry to the user. This collaborative combination of high-performance composite materials and the design flexibility of 3D printing embodies a new paradigm of orthotics and prosthetics. It facilitates the production of devices which are not just powerful and lightweight but accurately individualized to the user's anatomy and daily life, enduing in finally allowing function and quality of life that was beyond the realm of possibility to accomplish conventionally.

2.8 Post-Processing and Functional Testing

Reprocessing of 3D printed protheses to achieve functionality and comfort. Reprocessing of 3D-printed protheses aims to optimise post-print optimisation to enhance comfort, longevity, and user versatility. Following initial printing, the surface may be subsequently smoothed by sanding, polishing, or chemical smoothing to remove harsh textures that can lead to skin irritation [12]. For further comfort enhancement, soft-contact coatings like TPU or silicone liners can be introduced, making softer contacts (Zuniga, 2018). Structural optimisation comes as a further step, involving the use of computational modelling to optimise infill density and wall thickness, optimising strength against decreased weight Lastly, functional testing with the user—e.g., gait testing or grip testing—guarantees that the prothese performs effectively but also individualises to individual comfort requirements, allowing an iterative reprocessing and tailoring feedback loop.

Production procedure of a prosthesis typically involves these five steps, and after that, the patient can acquire a prosthesis which has his individual requirements and comfortable too.

3. Case Study

A 7-year-old boy named Alex was born with a congenital limb deficiency, missing part of his rigrt forearm. Classic prosthetic options were challenging for his family since child prostheses have to be replaced or resized every 12–18 months due to growth, and this added up to a staggering cost. The prices of a standard child myoelectric prosthesis varied between USD 8,000 to 15,000, which was out of reach for most families [3]. Furthermore, Alex's earlier prosthetics were uncomfortable due to ill-fitting, which made his skin irritated and restricted daily use. To correct these, a new style that incorporated artificial intelligence (AI) and 3D printing was used to design a cheap and tailored prosthetic limb.

It started with digital data capturing. Rather than the conventional plaster casting technique, surgeons employed a portable 3D scanner to digitally acquire the precise shape of Alex's residual limb in five minutes, in the absence of discomfort and with a highly precise digital template. AI-activated noise reduction algorithms treated this digital data, which erased errors like motion distortion and clothing artefacts [5]. EMG biosensors were also used to digitally capture Alex's muscle activity so that his resultant prosthesis could react intuitively to his movement. Biomechanical and muscle activity data thus integrated were sent to an AI program to optimize design.

AI-guided design phase incorporated Alex's physical data and individual activity demands. Rule-based programs also Computer-automatically set socket wall thickness to 3.5 mm, optimally balancing strength and lightweight characteristics [9], and the finger lengths to 70% of actual hand size to maintain a natural, realistic appearance and functional grasping dexterity [8]. AI further optimized joint alignment and simulated various grip and motion scenarios to anticipate likely compromise areas prior to actual production. For example, due to Alex's sportive lifestyle, his prosthetic hand was designed to have strong grip to handle his school and play activities and was made to be lightweight.

When the design was complete, it determined the choice of the materials. TPU (Thermoplastic Polyurethane) was chosen for the socket due to its flexibility and comfort. The mechanical parts of the hand were printed out of nylon (PA12) due to its strength. High-impact areas like the wrist joint received reinforcements of carbon fiber composite to give that much extra strength without a considerable increase in weight [14]. The prosthesis was printed out from a 3D printer, thereby cutting down the overall production time to a minimal period of three days, as opposed to conventional methods that took between 4–8 weeks [14].

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In addition, the cost of manufacturing went below 70%, rendering the device economically viable to Alex's family. Following the printing, post-processing methods were used to make it comfortable and functional. Chemical smoothing was used to treat the inner surfaces to avoid skin irritation, and a soft silicone liner to cushion sensitive areas [12]. Testing of the final device included gait and grip testing, and real-time feedback was returned to the AI system to make final adjustments. This iterative refinements process made the prosthesis a perfect fit and Alex's specific functional demands meetable.

As a result, Alex received a lightweight, functional, and affordable personalized prosthesis. The new device allowed him to perform daily tasks independently, such as writing, eating, and participating in sports. Because the entire design was stored digitally, future adjustments to accommodate Alex's growth would only require re-scanning and rapid reprinting at 30% of the original cost, significantly reducing long-term expenses. This case demonstrates how AI-driven design combined with 3D printing can revolutionize pediatric prosthetic production by drastically cutting production time, lowering costs, and delivering highly customized, comfortable solutions that improve quality of life for young patients and their families.

4. Limitation

While 3D-printed prosthetics offer significant benefits, such as rapid customization, cost-effectiveness, and improved user comfort, AI-driven design and manufacturing face several limitations.

4.1 Data Scarcity and Privacy Concerns

High-quality annotated datasets are crucial for training machine learning models to design personalized prosthetics. However, such datasets are scarce. For instance, a study involving 116 3D scans of residual limbs and corresponding socket shapes designed by 19 different prosthetists highlights the challenges in obtaining comprehensive and diverse datasets. Additionally, patient medical records and anatomical scans are sensitive, necessitating strict adherence to privacy regulations like HIPAA in the U.S., complicating data sharing and model validation.

4.2 Material Limitations

Typical 3D printing filaments, including polylactic acid (PLA), have been found to be restricted in strength and durability. Research has found that the fatiguing behavior of PLA has been found to vary based on raster angle and build rate. Although composite filaments including PLA-carbon fiber have demonstrated enhanced faturing life, these still cannot handle the severe demands of high-load activities like physical labor..

4.3 Regulatory Challenges

In the USA, 3D-printed limbs are medical devices that must be approved as medical devices by the FDA. The historical regulatory approach of the FDA was not built for flexible AI/ML technologies, making it difficult to assess the safety and effectiveness of AI-controlled limbs. In addition, standardized testing protocols for machine learning models are currently missing in this situation, and thus concerns over reliability and reproducibility arise.

5. Conclusion

This paper discusses individualized design of prosthetics based on artificial intelligence and 3D printing. It discusses systematically the major methods that this combination of technologies applies to solve the shortcomings of conventional prosthetics. It checks the value of application through real-world cases and finds out the disadvantages, and gives a reference for the extended design realization of customized prosthetics.

Technologically, the combination of AI and 3D printing transformed the conventional prosthetics sector, which is marked by mass-produced standardization, expensive prices, and extended lead times. Throughout the design and manufacturing process, 3D scanning and biosensors enable precise capture of patient physiological data, resolving the large errors and reliance on manual skill associated with traditional plaster modeling. AI, through rule-based algorithms and data learning, not only generates basic designs based on human anatomy that are safe and ergonomic, but also optimizes structures based on user needs (such as the high-intensity demands of athletes and the growth needs of children), reducing trial-and-error costs. 3D printing, with its material flexibility (e.g., TPU for general use and carbon fiber for specialized needs) and rapid manufacturing capabilities, has shortened production cycles from the traditional 4-8 weeks to approximately 3 days, reducing costs by 50%-70%, and enabling efficient iterations of the "design-adjust-remanufacture" process.

The case of 7-year-old Alex further demonstrates the practical value of this technology. Addressing the pain points of frequent prosthetic replacement and the high cost of traditional products for children, AI and 3D printing not only provide customized prosthetics that fit the residual limb, are comfortable and durable, and meet the needs of daily activities and growth, but also, through the reusability of digital design, reduce subsequent adjustment costs to 30% of the original cost, significantly alleviating the family's financial burden. This case study clearly demonstrates that the combination of AI and 3D printing is not simply a technological overlay, but rather, driven by patient needs, truly achieving the goals of personalized, low-cost, and fast-delivery prosthetics. It provides a viable solution for individuals with limb loss (especially children, athletes, and other special groups) to restore their ability to function and improve their quality of life.

However, current technology still has limitations that need to be overcome. On the data front, high-quality annotated data from "stump scans + user feedback" is scarce, and patient privacy regulations (such as HIPAA) restrict data sharing, hindering the generalization capabilities of AI models. On the material side, conventional 3D printing materials like PLA lack durability and are difficult to meet high-intensity usage scenarios, while the application range of high-performance materials like carbon fiber still needs to be expanded. On the regulatory side, the existing medical device approval system (such as FDA certification) lacks standardized processes for AI-driven dynamic design, which may slow the implementation of this technology.

In the future, if an "anonymous data sharing alliance" can be established to address data issues, promote the development of new wear-resistant, low-cost biomaterials, and collaborate with industry and regulatory authorities to develop specific testing standards for AI-powered prosthetics, AI and 3D printing technologies will undoubtedly play a greater role in the field of personalized prosthetics. In the long run, this technology will not only enable more low- and middle-income groups and people with special needs to obtain suitable prosthetic limbs, but may also be upgraded in the direction of "smart prosthetic limbs" (such as combining with the Internet of Things to achieve real-time gait adjustment), ultimately pushing limb assistive devices from "functional repair" to "experience optimization", bringing fairer and higher-quality health services to the 57 million people with limb loss worldwide (WHO, 2023).

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