The *3D Printing Center for Health*: Advancing Personalized Healthcare Solutions Through Additive Manufacturing

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Abstract: The *3D Printing Center for Health* is a non-profit association dedicated to advancing personalized healthcare through the innovative application of 3D printing technology. By using a patient-centered, co-creation methodology, the Center collaborates with patients, healthcare professionals, and engineers throughout the design and development process. This approach enables the production of cost-effective, highly customized medical devices, including prosthetics, orthotics, assistive devices, and anatomical models tailored to meet the unique anatomical and functional needs of each patient. While partnering with hospitals and rehabilitation centers, the Center addresses accessibility and affordability gaps often encountered in traditional healthcare, making advanced solutions more widely available. Clinical studies have shown substantial improvements in patient mobility and satisfaction, as well as a significant reduction in production costs due to the efficiency of additive manufacturing. This paper provides an overview of the Center's mission, methods, and main achievements, highlighting its contributions to healthcare innovation and improvements in patient-specific care through advanced 3D printing technologies. The Center's commitment to social responsibility, innovation, and patient-specific design is setting new standards in rehabilitative care and establishing a foundation for future advancements in accessible, high-quality healthcare solutions.

1 INTRODUCTION

Additive Manufacturing, also known as Three-dimensional (3D) printing technology, has been emerging as a transformative tool in healthcare, as it enables the production of highly customized, patient-specific medical devices that traditional manufacturing methods often cannot achieve (Pereira et al., 2022; Pathak et al., 2023; Nizam et al., 2024). 3D printing applications in healthcare range from creating prosthetic limbs and orthotic devices to producing detailed anatomical models for surgical planning and education. By building objects layer by layer from digital models, 3D printing allows for unparalleled precision and customization, significantly enhancing the quality and accessibility of medical solutions (Tian et al., 2021).

Despite these advancements, significant gaps remain in the healthcare sector, especially concerning common prosthetic and orthotic solutions. Usually, these devices are costly and often lack personalization, leading to discomfort and limited functionality for patients, which results in high rejection rates (Kumar Banga et a. 2021). Furthermore, access to affordable, high-quality rehabilitation tools is limited, particularly for pediatric patients who require frequent adjustments due to children's development (Pathak et al., 2023).

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To address these challenges, the *3D Printing Center for Health* association was established with the mission of developing accessible, cost-effective, and highly customized healthcare solutions using advanced 3D printing techniques. This non-profit association brings together a multidisciplinary team of engineers, healthcare professionals, and researchers who collaborate on the design and implementation of tailored medical devices. By working closely with hospitals and rehabilitation facilities, the *3D Printing Center for Health* ensures that these innovations are implemented in real-world sceneries, thereby directly addressing the needs of patients who, otherwise, would have limited access to specialized care.

This paper aims to present an overview of the *3D Printing Center for Health*, highlighting its primary projects and the methodologies that guide its research and applications. It presents an overview of the Center’s mission, methodologies, and key achievements, underscoring its role in advancing healthcare innovation and patient-specific care through 3D printing. Through a series of case studies, the paper illustrates the Center’s impact on patient care, demonstrating how 3D printing can be leveraged to create affordable and tailored healthcare solutions that bridge critical gaps in traditional healthcare delivery.

2 MATERIALS AND METHODS

The *3D Printing Center for Health* employs a structured, dynamic co-creation methodology that keeps the patient at the heart of every stage of the development process (Clanchy et al., 2024). This patient-centered, adaptable approach is designed to evolve with the patient's needs over time, ensuring continuous alignment with both individual and clinical requirements. Multidisciplinary collaboration among engineers, healthcare professionals, researchers, and patients enable the development of devices that are uniquely tailored to the needs of each patient (Silva et al., 2024). The Center’s mission is to establish itself as a leader in promoting health and functional independence through innovative 3D printing technologies. By focusing on developing customized, accessible solutions, the Center seeks to empower individuals with motor disabilities and other health needs, underscoring its commitment with the advance of patient-centered healthcare. The Center’s work is composed of three main projects: 3D Anatomical Printing, e-NABLE 3D Printing Center for Health and Motion Seeker.

a) 3D Anatomical Printing

This project focuses on the construction of anatomical models based on medical imaging data, with a particular reliance on Computed Tomography (CT) scans and Magnetic resonance imaging (MRI). CT imaging provides cross-sectional data that enables the creation of precise, three-dimensional representations of complex anatomical structures. These structures can then be 3D printed, whether by Fused Deposition Modeling (FDM), using mainly Polylactic Acid (PLA) or through Vat Photopolymerization (SLA) using Resins. These 3D-printed models are essential for surgical planning, allowing clinicians to visualize and assess patient-specific anatomy in a tangible way. In addition to surgical planning, these models are invaluable for educational purposes, providing trainees and medical students with realistic, patient-specific models for hands-on learning. Moreover, these models can be used to explain to the patients their health problems and how the medical team is going to approach them, therefore comforting the patients. Overall, the detailed visualization enabled by CT-based 3D printed models enhances the clinicians’ ability to anticipate challenges and devise tailored surgical approaches, ultimately improving patient outcomes and procedural success rates.

b) e-NABLE 3D Printing Center for Health

This project is dedicated to the development of custom prosthetic devices, which can be precisely adapted to address the specific motor dysfunctions and needs of each patient. Through open-source designs from the e-NABLE organization (https://enablingthefuture.org), the Center’s team leverages a foundation of shared knowledge to deliver highly individualized solutions. These prosthetics are printed with rigid and flexible materials, usually PLA and Thermoplastic Polyurethane (TPU), respectively. These materials are chosen for their unique properties. PLA, a biodegradable thermoplastic derived from renewable resources like corn starch, offers rigidity and stability, making it ideal for structural components of prosthetics that require durability and shape retention. TPU, a flexible and elastic thermoplastic, is used where adaptability and comfort are paramount, such as in joint areas or grip-enhancing sections of the prosthesis.

The design process involves exploring a range of mechanical functionalities that maximize ease of use and patient comfort.

Through this approach, the project not only addresses the immediate functional needs of patients but also paves the way for next-generation prosthetic devices that are adaptable, comfortable, and responsive to each individual's unique requirements.

c) Motion Seeker

The Motion Seeker project is focused on designing and developing customized assistive devices to enhance functional independence for patients with physical disabilities. Each assistive device is meticulously tailored to support specific activities, with the goal of empowering users to completely engage in their daily tasks and social interactions. The design process is conducted entirely by the Motion Seeker team, consisting of engineers, healthcare professionals, and designers who collaborate closely with end-users and their families to ensure that each device meets their unique functional needs. These solutions are tailored to assist specific activities, ensuring practical applicability and user comfort. As with the developed prostheses within the scope of e-NABLE 3D Printing Center for Health, the Motion Seeker devices are predominantly printed with PLA and TPU. However, more complex solutions may be printed with higher performance materials, like Acrylonitrile Styrene Acrylate (ASA), Acrylonitrile Butadiene Styrene (ABS) or Nylon.

Systematic Co-Creation Process

The following steps are uniformly applied across all projects to ensure consistency in device development:

1. Identification the Requirements: This initial phase is crucial for establishing a clear understanding of the specific needs and functional goals of each assistive or prosthetic device. The requirements are identified through a structured co-creation methodology, which, as previously described, actively involves patients, clinicians, and caregivers in the decision-making process. By engaging all stakeholders from the outset, this approach ensures that the device aligns with the user's unique anatomical, functional, and lifestyle needs. During this stage, detailed discussions and assessments are conducted to gather insights into the patient's daily challenges, preferred usage scenarios, and any existing limitations with traditional devices. The co-creation process involves gathering both qualitative and quantitative data. Qualitative insights are collected through interviews and questionnaires with patients and healthcare providers, while quantitative measurements, such as anatomical measurements, range of motion and strength assessments, are performed to ensure that the functional requirements of the device are fully understood. This collaborative step is essential for ensuring that the project is precisely tailored to each patient and provides a foundation for the following design and development phases. By defining these requirements comprehensively, the team establishes a roadmap for the next steps. This systematic approach ensures that each device development is highly customized, patient-centered, and responsive to the real-world needs of users, setting the stage for a successful design outcome.

2. Image Processing/3D Scanning: This phase involves capturing patient-specific anatomical data through advanced 3D scanning techniques to ensure the precision required for a customized fit and functionality of the device. Using technologies such as CT, MRI, or high-resolution optical scanning, detailed digital representations of the patient's anatomy are obtained. These imaging techniques allow for precise measurements of bone structure, soft tissue contours, or any unique anatomical variations that may impact device design. Once acquired, the scanned data undergoes initial image processing to refine and optimize the anatomical model. This includes segmentation, where specific areas of interest (such as bones, muscles, or joints) are isolated and refined, ensuring that only the most relevant anatomical details are used in the design process. This processing step is critical for removing noise and highlighting key structural features, which allows for greater accuracy in subsequent modelling stages. In some cases, multiple imaging modalities are combined to create a comprehensive 3D model that captures both the internal and external anatomy. For instance, CT scans may provide detailed skeletal structure, while MRI data can add soft tissue information, producing a more holistic anatomical model. This level of detail is particularly valuable for complex cases, enabling the design of devices that closely conform to the patient's anatomy and offer improved comfort and functionality. The resulting 3D model is then imported into Computer-Aided Design (CAD) software.

- **3. Computer-Aided Design (CAD) Modelling:** In this phase, the anatomical data captured through 3D scanning is transformed into an accurate digital model using Computer-Aided Design (CAD) software. The *3D Printing Center for Health* typically relies on Autodesk Fusion 360 (https://www.autodesk.com) for creating patient-specific medical devices. Fusion 360s advanced capabilities allow the design team to replicate anatomical contours precisely, ensuring that the digital model reflects the unique dimensions and structural nuances of each patient's body. The CAD model functions as a flexible template for customization, enabling the design team to adjust the device's shape, size, and functional elements to meet the specific needs identified during the requirements-gathering phase. This customization includes designing features to support movement, applying ergonomic principles to enhance comfort, and adding adjustable components as necessary. Fusion 360 collaborative tools further allow for real-time design adjustments based on continuous feedback from both patients and clinicians, ensuring that the model remains closely aligned with clinical requirements and user preferences. Through an iterative design process, the digital model is refined through multiple cycles. Feedback from clinicians addresses functional aspects, such as stability and support, while patient input focuses on comfort, fitting, and aesthetic preferences. This iterative cycle enables the team to make precise adjustments that optimize the device's usability and effectiveness for real-world application. Once the CAD model is finished, it undergoes through final validation within the software to ensure structural integrity and compatibility with 3D printing specifications. The validated model is then prepared for the next phase, material selection and 3D Printing. This CAD modelling phase is essential to achieve a highly customized, user-centered device, as it provides the digital framework that guides fabrication.

4. Material Selection and 3D Printing: Suitable materials are chosen based on the device's intended function and patient needs. The majority of materials used in device fabrication include PLA and/or TPU, selected for their specific properties suited to patient needs and the intended function of each device. PLA provides rigidity and stability, ideal for structural components, while TPU offers flexibility, making it suitable for areas requiring greater adaptability and comfort. Devices are fabricated using FDM, the most common 3D printing technology, which enables rapid prototyping and allows for iterative adjustments throughout the design process. This ensures each device meets high standards of functionality and patient comfort.

5. Prototype Testing with Healthcare Professionals and Patients: This phase is dynamic and iterative, centered on testing the initial prototype with both healthcare professionals and patients to ensure it meets all functional, clinical, and occupational needs. The first prototype is rigorously evaluated for fitting, comfort, and usability in real-life applications, with extensive feedback gathered from all participants, both from interviews and from the use of the System Usability Scale (SUS). (Bangor, Kortum, and Miller 2008) This feedback is invaluable, as it allows the team to make necessary design adjustments that better align with the unique requirements of each patient and the clinical expectations. If modifications are needed, the design is refined, reprinted, and subjected to further rounds of testing. This cycle of adjustment, reprinting, and retesting continues as needed, enabling the team to optimize the device until it achieves the desired outcomes. Throughout this process, the interests of the patient, including both clinical and occupational aspects, remain at the core of decision-making, ensuring that the final device not only fulfills technical specifications but also enhances the patient's quality of life and independence. This collaborative testing phase is essential for balancing clinical functionality with patient comfort, as the active involvement of patients and clinicians ensures that the final device is as practical and effective as possible. The comprehensive methodology enables the Center to produce cost-effective, high-quality devices tailored to address specific clinical needs while maintaining rapid adaptability to feedback and continuous improvement. The Center's projects leverage a structured, dynamic co-creation methodology, ensuring each device meets patient-specific anatomical and functional requirements. Through a collaborative process involving patients, clinicians, and engineers, device requirements are iteratively refined, with adjustments made based on ongoing feedback and clinical testing.

By applying this methodology consistently across all projects, the *3D Printing Center for Health* ensures the production of cost-effective, high-quality devices that meet specific clinical and patient needs. This systematic approach enhances the Center's ability to adapt designs in response to feedback, enabling continuous improvement and alignment with real-world requirements.

3 RESULTS

The *3D Printing Center for Health* has achieved significant impact through its three main projects, with measurable improvements in patient care and functionality.

a) 3D Anatomical Printing

Anatomical models created through this project have been used in various hospitals, providing clinicians with detailed, patient-specific visual aids for surgical planning and training. Different anatomical structures, including a thoracic cage model printed in PLA (Figure 1), have been produced to support hands-on training exercises. Feedback from medical professionals indicates that these models enhance precision in complex surgical procedures by improving anatomical visualization and enabling the medical team to practice techniques in a realistic and controlled environment.

Figure 1: Thoracic cage model printed in PLA.

b) e-NABLE 3D Printing Center for Health

The e-NABLE 3D Printing Center for Health has successfully developed and delivered custom prosthetic devices specifically designed for pediatric upper-limb applications, providing vital support for numerous patients with motor impairments. Using open-source models from the e-NABLE organization as a foundation, the Center customizes each prosthesis to address the unique anatomical and functional needs of each child. This approach allows for the production of prostheses that enhance comfort, functionality, and adaptability, promoting greater independence and confidence in daily activities.

To meet the specific requirements of different types of amputations, the Center has developed various prosthetic models, including transcarpal (Figure 2), transradial (Figure 3), and transhumeral prostheses (Figure 4).

Each type is tailored according to the level of amputation, ensuring an optimal fit and alignment with the patient's remaining limb structure. This customization process enables children to perform tasks more effectively and comfortably, with designs that accommodate their growth and evolving needs.

Figure 2: Prosthesis designed for a child with a transcarpal amputation.

Figure 3: Prosthesis designed for a child with a transradial amputation.

Figure 4: Prosthesis designed for a child with a transumeral amputation.

By integrating a patient-centered approach and advanced 3D printing technology, the Center is able to offer accessible, cost-effective prosthetic solutions that significantly improve the quality of life for pediatric patients with upper-limb deficiencies. The SUS results were 95, 85 and 98 respectively which show that this approach works. Furthermore, long term monitoring showed that all patients still use the prosthesis, contrary to the normal rejection rates after 6 months (Resnik L., Borgia M., Biester S., Clark M.A., 2021), even when compared with the E-Nable standard models.

With these prostheses, children are now able to perform tasks and gestures they had previously been unable to accomplish.

Currently, the Center is actively engaged in research focused on the development of myoelectric prosthetics, aiming to create devices that offer enhanced control and responsiveness. Ongoing research on myoelectric prosthetics suggests promising future applications, with potential for more intuitive, user-friendly designs that could further improve patient autonomy.

c) Motion Seeker

One of the key projects under the *3D Printing Center for Health*, the *Motion Seeker*, exemplifies the transformative potential of 3D-printed assistive devices. This project focuses on developing devices that enable patients to regain independence in performing daily tasks. Devices developed within this framework have notably improved the ability of patients with motor handicaps to engage in previously challenging activities, such as playing musical instruments or using everyday objects (Figure 5).

Figure 5: Assistive device for daily tasks.

These devices are specifically designed from the ground up to ensure maximum functionality and comfort, from the initial conceptualization and design phase up to the final 3D printing process.

The Center's approach to designing devices based on individual anatomical specifications ensures optimal performance across a range of tasks, thus improving the patient's overall independence.

Feedback from both patients and caregivers has been overwhelmingly supportive, with reports indicating a marked improvement in the ease of use and comfort of these devices. Since January 2022 through October 2024, the Center has developed a total of 82 devices, representing 43 unique designs, which have helped 78 patients across 9 services from various hospitals. Patients and caregivers have expressed particular, appreciation for the adaptability of these devices, noting how seamlessly they can be used for different tasks, further emphasizing their effectiveness in daily life. The combination of tailored designs and advanced manufacturing processes has led to assistive devices that not only meet functional requirements but also provide long-term comfort, contributing to enhanced patient satisfaction and overall well-being, with an overall SUS value of 91.

The *3D Printing Center for Health* has made significant advancements in medical device development, demonstrating measurable clinical and economic benefits through its innovative applications of 3D printing technology in healthcare.

Figure 6 illustrates the distribution of project activity within the *3D Printing Center for Health* across its three main initiatives.

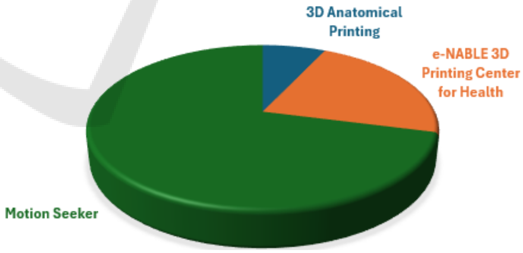

Figure 6: Distribution of activity across each project.

The data indicate that most of the Center's efforts, 71%, are concentrated on the Motion Seeker project, which focuses on developing customized assistive devices aimed at improving functional independence for patients with physical disabilities. The e-NABLE 3D Printing Center for Health project, dedicated to creating personalized prosthetics primarily for pediatric patients, represents 22% of the Center's work. Finally, 3D Anatomical Printing, which involves creating detailed anatomical models for surgical planning and educational purposes, accounts for 7% of the Center's activities. This distribution reflects the Center's strategic emphasis on assistive devices for enhancing patient autonomy, followed by efforts in prosthetics and anatomical modelling.

Among the Center's most notable achievements, clinical studies indicate a remarkable 90% improvement in patient mobility among users of 3D-printed rehabilitation devices. This improvement has been attributed to the highly customized designs, which align closely with individual anatomical and functional needs compared to standard devices available on the market. Additionally, the Center's use of Additive Manufacturing has led to a 30% reduction in production costs, an achievement that greatly enhances the affordability and accessibility of essential rehabilitation solutions.

The impact on patients has been equally profound, with user testimonials reflecting a 95% satisfaction rate. Patients consistently report enhanced comfort and functionality, emphasizing how these devices are helpful in their daily activities. For many users, these assistive devices and prostheses have enabled them to perform tasks and gestures that were previously unachievable, underscoring the Center's success in addressing both physical and psychological needs. The patient-centered approach, focusing on the customization and refinement of 3D-printed devices, has proven to be highly effective, reinforcing the *3D Printing Center for Health*'s role as a leader in advancing patient care through innovative, accessible, and responsive healthcare technologies.

4 CONCLUSIONS

The *3D Printing Center for Health* has effectively demonstrated the transformative potential of additive manufacturing in healthcare through the creation of customized, functional, and accessible assistive devices. By employing a patient-centered design approach and leveraging advanced 3D printing technologies, the Center has elevated both the quality and adaptability of medical devices, aligning them closely with the specific clinical and occupational needs of diverse users. Furthermore, the Center addresses critical gaps in traditional healthcare, particularly for underserved communities, by creating high-quality, customized, and affordable devices that enhance users' quality of life and promote social inclusion. Future initiatives include expanding research into myoelectric devices with electromyographic control for real-time responsiveness and exploring biocompatible smart materials to enhance adaptability and durability. Through this commitment to innovation and patient-centered design, the 3D Printing Center for Health is setting a new standard in rehabilitative care, advancing healthcare technology, and promoting equity across patient populations. Future initiatives include developing myoelectric devices and exploring biocompatible materials to enhance adaptability and durability. Through this commitment to innovation and accessibility, the Center sets a new standard in rehabilitative care.

Additionally, the *3D Printing Center for Health* ensures the performance and safety of all devices by adhering to local and international regulatory requirements for medical devices. Each device undergoes rigorous testing for structural integrity, functionality, and safety before being approved for clinical use. The Center collaborates with healthcare institutions to guarantee compliance with applicable legal frameworks. Additionally, a thorough risk management process is implemented to identify and address potential hazards throughout the development cycle. This approach ensures that all devices meet high standards of safety, reliability, and efficacy, reinforcing the Center's commitment to advancing patient-centered healthcare solutions.

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