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Design and Implementation of a Polar-type 3D Printer for Highly Optimised Manufacturing of Prosthetic Sockets in LMICs

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INTRODUCTION

It is estimated that approximately 57.7 million people worldwide live with limb loss [1]. These are mostly concentrated in low- and middle-income countries (LMICs), where healthcare provision is limited and the skilled workforce required to manually produce prosthetic sockets is too small to meet this huge clinical need. Manufacturing prosthetic sockets using conventional casting is a time consuming and labour intensive process, involving the patient making multiple visits to the clinic over a number of weeks [2]. Once cast, it can take up to a day for a technician to manually produce a customised socket. There is therefore an urgent need for a fast, highly automated, and low cost solution to the manufacture of personalised prosthetic sockets.

3D printing is often proposed as a way of meeting these objectives [3]. A 3D printer can produce one-off objects with limited setup time and cost, from affordable and readily available materials, with virtually no human intervention between the start and end of the process [4]. Previous research has also investigated the use of 3D scanners to automatically generate sockets from the geometry of a residuum, further reducing the workload of skilled technicians, increasing throughput [5].

Despite these advantages, a number of technical challenges have prevented the widespread use of 3D printed prosthetic sockets in LMICs. The limited mechanical strength of 3D printed sockets has been previously highlighted [6],

Firstly, the mechanical strength of 3D printed prosthetic sockets has been called into question by studies that have observed catastrophic failures of 3D printed sockets [6], and even those that have been able to meet the ISO 10328 standard for mechanical durability have required significant iteration before meeting this requirement [7]. Additionally, whilst much faster than manually produced sockets, current 3D printers can still take up to 48 hours to produce a full sized, lower limb socket, meaning that a large and expensive print farm would be needed show any meaningful benefit [8].

MATERIALS AND METHODS

Polar 3D printer

A 3D printer based on polar kinematics was designed and built, with the objective of being highly optimised for producing prosthetic sockets by significantly reducing the print time of a prosthetic socket compared to more conventional 3D printers (Fig. 1). Two key technical decisions have been made to support this: Firstly, the polar kinematics model is intrinsically well suited to producing cylindrical-shaped prosthetic sockets. This is because, unlike conventional Cartesian 3D printers, the motors controlling the position of the print head do not need to accelerate and decelerate to create circular shapes - the print bed can run at full speed for the duration of the print whilst the print head makes much smaller moves across the wall thickness of the socket. Secondly, the proposed 3D printer has two print heads, each with a 1.4 mm nozzle. These can either be controlled independently or linked together in software to give the printer an effective nozzle diameter of 2.8 mm as demonstrated in Fig. 2. This gives a maximum volumetric flow rate of approximately 180 mm^3s^{-1}, and additionally provides the ability to print using a combination of materials to achieve improved socket comfort or durability.

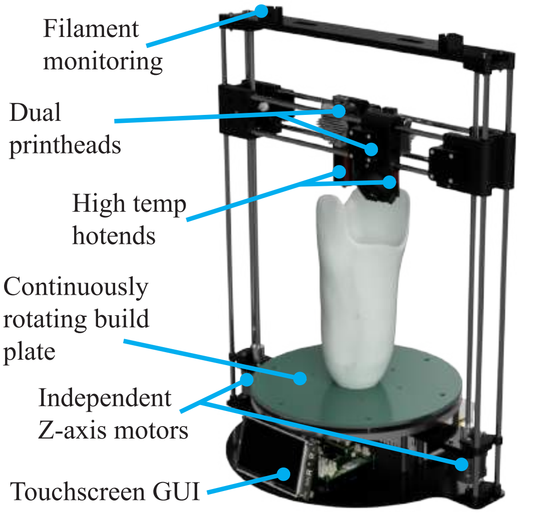

Fig. 1. A 3D CAD render of the prototype polar 3D printer with a socket shown for scale

Concerns regarding mechanical strength can be addressed either through the use of advanced materials, or through modifications to the printing process itself. The prototype polar 3D printer supports both. Advanced materials (PEEK, polycarbonate, nylon and PMMA) are supported by the use of E3D SuperVolcano hotends with maximum supported nozzle temperatures of 500° C. A heated bed with a maximum rated temperature of 140° C has also been included. These materials have better mechanical properties than commonly used PLA and ABS materials and are more likely to meet the strength requirements of ISO 10328. Additionally, the provision of multiple hotends raises the possibility of producing composite sockets using different materials, as well as investigating different printing strategies (for example, depositing plastic in interwoven spirals).

In order to accommodate transfemoral sockets which can be too large to produce on typical FDM 3D printers, the prototype 3D printer has a build volume of 300 mm (dia.) × 350 mm (h).

Software and operation

Whilst conventional (cartesian) slicing software is compatible with the prototype 3D printer (the conversion to polar kinematics happens in firmware) a custom model slicer was developed based on Blender to allow better optimisation and control of the toolpaths to make the best use of the polar model.

In this software, the 3D model is first imported to Blender and placed on the virtual horizontal plate with the model's center of gravity over the build plate center. Next, the model is sliced into horizontal layers in steps equal to the desired layer height (initially 1mm). Each slice consists of two contours that are labeled as inner and outer contours based on their respective lengths. It should be noted that there is no correspondence between inner and outer contour vertices - contours may have an unequal number of vertices with unstructured distribution. A solid infill (generally considered necessary to meet the ISO 10328 requirement for lower limb prosthetic durability [7]) is generated by performing edge slides from the inner contour toward the outer. Each vertex of the sliding edge is moved along a direction defined by the normals of adjacent edges and an outer edge it is projected on. The slide distance is equal to the material deposition thickness. The edge slide is constrained by the outer edge. This ensures that the inner contour is shaped as closely to the source model as possible, ensuring the best possible fit and finish of the mating edge whilst taking full advantage of the continuous, full speed rotation capability of the polar 3D printer.

RESULTS

A prototype polar-type 3D printer and associated slicer software was built and is currently undergoing initial technical testing and evaluation. Initial performance simulations indicate that printing a sample socket measuring 130 mm (dia.) × 280 mm (h) with a 10 mm wall thickness, at a very conservative but sustained 200 mms^{-1} print speed (approx. 30 rpm rotation speed), would take 50-60 minutes. For comparison, the Modix BIG40 (2020) would take 31.5 hours to produce the same part using a standard 0.4mm nozzle using preset 'fast' settings. A Prusa XL (2023) would take 15.5 hours with a 0.8 mm nozzle, 0.55 mm layer height and input shaping.

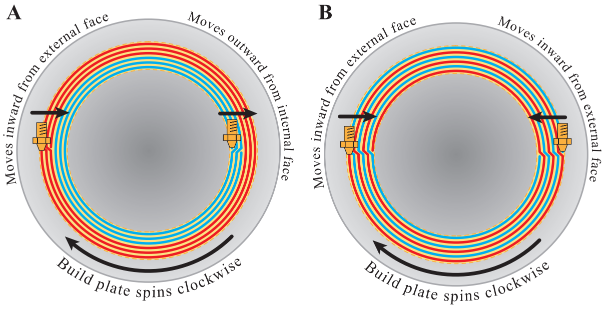

Fig. 2. Diagram showing the motion paths employed by the dual extruder, polar 3D printer in A) concentric mode and B) spiral mode

DISCUSSION

The print time simulation above suggests that this highly-optimised polar 3D printer could demonstrate a significant speed improvement over the current state-of-the-art when used to produce prosthetic sockets. Further testing will evaluate average print times for sockets for a variety of common amputations and evaluate the mechanical strength of sockets produced using different materials and print strategies, with an emphasis on identifying combinations that reliably meet the ISO10328 standard whilst maintaining the speed, cost and availability benefits associated with 3D printing.

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