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4D Printing of Magnetically Functionalized Chainmail for Exoskeletal Biomedical Applications

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Chainmail fabrics manufactured by selective laser sintering 3D printing have been magnetically functionalized to create a lightweight, 4D printed, actuating fabric. The post-processing method involves submerging the porous prints in commercial ferrofluid (oil-based magnetic liquid), followed by drying under heat. The actuation of the chainmail has been simulated using a rigid multi-body physics engine, and qualitatively matches experiment. Such magnetically actuating fabrics have potential to make thin, lightweight and comfortable wearable assistive devices.

INTRODUCTION

The function of wearable assistive devices is to support and improve the mobility of the disabled and the infirm, as well as those recovering from injuries. The design of such exoskeletal devices generally requires embedded actuators to provide mechanical support of limbs and joints, which are ideally fabricated using soft materials so as to be conformable to the human body [1]. Many different types of soft actuators have been investigated for this application such as swellable hydrogels [2], granular media [3], electroactive polymers [4], and pneumatic systems such as fluidic elastomer actuators [5]. However, none of these are ideal. Some require tethering to auxiliary equipment which limits their scope in terms of the range of mobility offered to the user. Others require high voltages to function [6] rendering them impractical for a close-to-skin garment. Another problem faced by those designing wearable assistive devices is fitting: how to fabricate the device to fit the user and to tune the mechanical actuation to respond to their particular needs. At present most devices are hand-made and need to be customized to fit.

4D printing is a manufacturing technique that has the potential to address both these problems. It is a process of using 3D printing to produce materials with programmable functionality. Since its introduction by its pioneer Skylar Tibbits in 2013 [7], materials engineers have already created some innovative designs for simple actuating shapes which morph in response to stimuli like moisture or heat [8]. This new field is in its infancy: at present there are limited stimuli, and the structures produced are often mechanically weak with slow response times [6]. Nevertheless it is clear that the design of a wearable assistive device using computer aided design (CAD) allows it to be computationally fitted to the geometry of a user's limb by making use of 3D scanning. The wearable assistive device can then be 'programmed' to suit the needs of the user by simulating the mechanics of actuation using a computer model [9]. The final stage of 4D printing would be create an orthotic which is bespoke to the user both in terms of fit and mechanism.

In this paper we show proof-of-principle of the 4D printing aspects of this approach. We build on our past work creating flexible chainmail fabrics with variable stiffness [9]. We show that a programmable chainmail structure can be designed, its mechanical behaviour simulated, and then 4D printed in a two-stage process to create a magnetically functionalized chainmail ("Fe-mail").

MATERIALS AND METHODS

All 3D prints were digitally designed in Fusion 360 from Autodesk (Autodesk.com). The generated .stl files were processed using Materialise Magics (www.materialise.com) by technicians at B.Made 3DP in UCL's Bartlett School of Architecture. They were selective laser sintered (SLS) in Nylon 12 – PA 2200 using a Formiga EOS P100 (www.eos.info). Fresh and recycled powder was used in a 50:50 ratio. Solid rectangular test-pieces (60mm x 24mm x 2mm) were printed, in order to image the surface of the material, as well as simple three-layer cube chainmail, with dimensions shown in Figure 1.

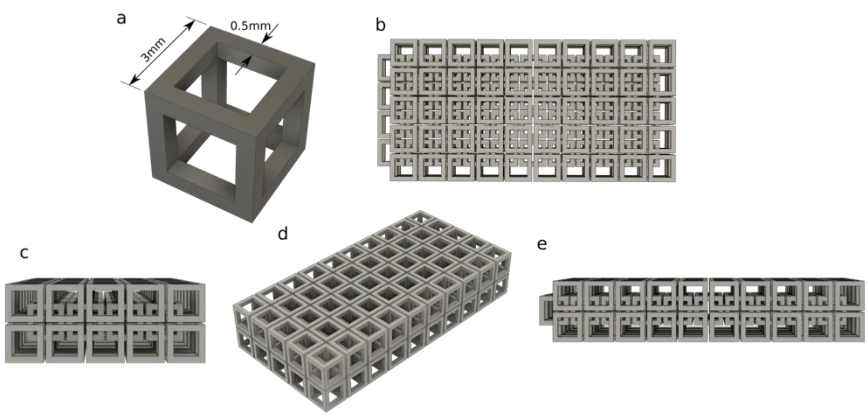

Figure 1: (a) Geometry of a cube link, (b) top view, c) end view, d) perspective view and e) side view of the CAD chainmail.

Post-processing starts with submerging a nylon print in a petri-dish which is filled with ferrofluid, and leaving it to rest for 30 minutes. After this time, samples are lifted from the ferrofluid, and excess removed with a paper towel. All samples are dried for 48 hours in a drying oven at 90 °C prior to use, see Figure 2. Ferrotec EFH1 ferrofluid (www.ferrotec.com), batch number 5060451570007, was used to functionalise the nylon prints. The average magnetic particle size in the ferrofluid is approximately 100Å (10 nm).

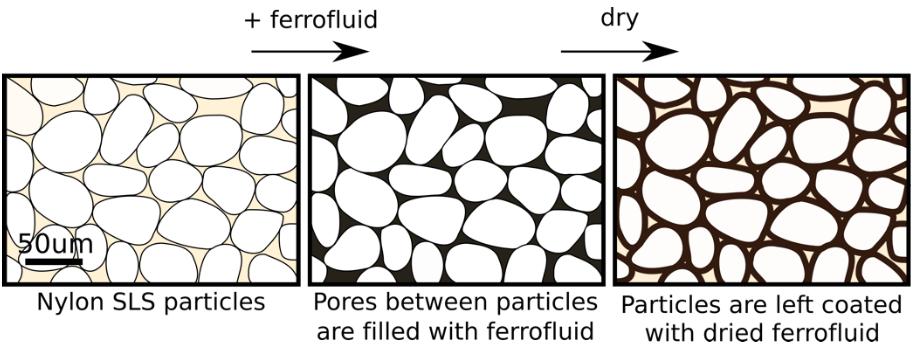

Figure 2: Schematic cross-section of the post-processing method, where SLS prints were dipped in ferrofluid and then dried. The process deposits magnetic nanoparticles in the form of dried ferrofluid throughout the porous material.

The mechanics of Fe-mail was modelled using the rigid body simulation with collision detection conducted with the standard Bullet Physics Engine (bulletphysics.org). The mesh and Bullet objects/constraints were initialized and the simulations performed using Blender (for full details see our previous work [9]). For these proof-of-principle simulations, a surface constraint perpendicular to one end of the Fe-mail was added, and given an attractive plane forcefield to simulate magnetic force (magnetic : gravitational force = 150 : 1). The simulations were experimentally verified using a neodymium permanent magnet (field strength 0.4T) and a section of post-processed Fe-mail of 10x5x3 link geometry.

RESULTS

The post-processing method resulted in a matte brown solid which was 4.4 wt% dry ferrofluid. Under the microscope, nylon powder particles were still clearly visible in the pre- and post-processed material (Figure 3a, 3b). The optical micrographs of post-processed Fe-mail show that the links are evenly distributed with ferrofluid, and do not get stuck together with ferrofluid on the surface (Figure 3c, 3d).

The rigid multi-body physics engine simulations were well-matched with experiment (Figure 4). Without an external magnetic field but fixed in space at one end, the simulated Fe-mail fabric drapes downwards. The curvature of the simulated draped Fe-mail is slightly greater than that of the experimental sample, and this is attributed to the post-processed Fe-mail having larger dimensions due to surface coating of ferrofluid.

With an applied magnetic field perpendicular to the end of the Fe-mail, both the simulated and experimental Fe-mails actuate into a stiff structure which resists the pull of gravity, and remain horizontal. The mechanism by which this stiffness transition occurs is that all cubes are attracted to the magnet, resulting in contact between links; it is the frictional forces between the links overcoming the downwards force of gravity that modulates the effective stiffness of the fabric.

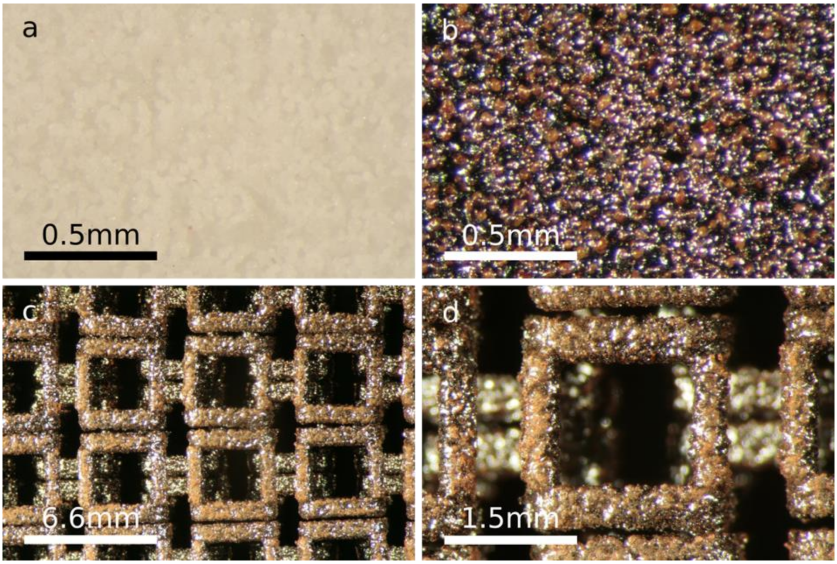

Figure 3: Optical micrographs of a) Unprocessed SLS print b) Post-processed SLS print c) Post-processed Fe-mail d) Post-processed Fe-mail link.

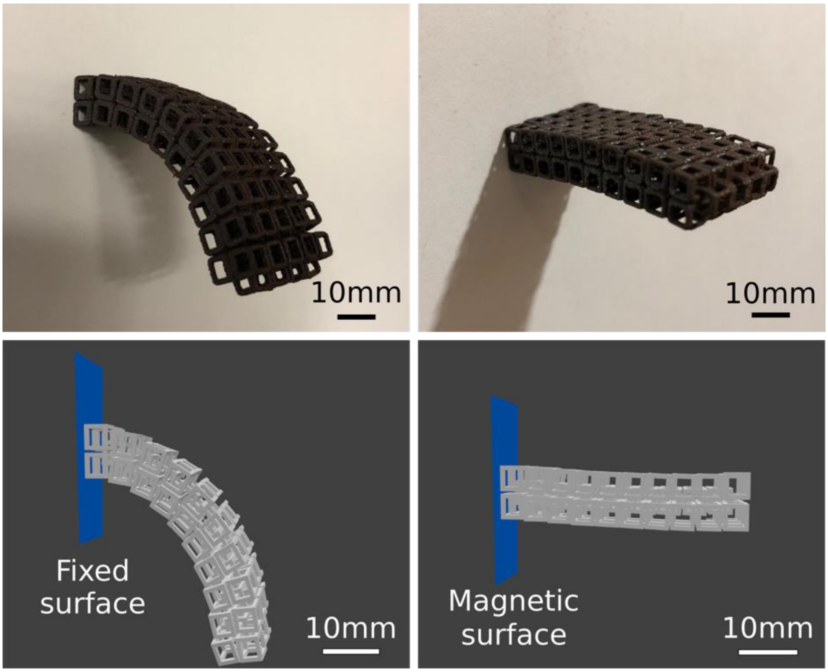

Figure 4: Experimental (a, b) and simulated (c, d) post-processed Fe-mails, in the unactuated (a, c) and actuated (b, d) states.

DISCUSSION AND CONCLUSIONS

This study demonstrates the potential of using computer-aided design and simulation to design and optimise actuating fabrics which can then be 4D printed. In particular, our method for incorporating nanoparticles into the printing process is novel and is not limited to magnetic actuation. Our process is well-suited to creating bespoke fabrics for use in wearable assistive devices such as orthotics which are specific to a user's needs. As an example, Figure 5 shows the design of an actively-stiffening fabric which could replace the passive metallic splints conventionally used in such supports. This actively-stiffening fabric could be embedded in a simple joint brace, to provide a section with controllable stiffness. There are many technical issues still to resolve with this technology, such as how to control the device with a magnetic field in-situ, and we will report on progress in future publications.

Figure 5: Schematic of an actively-stiffening wrist-brace. In such a device, an actively-stiffening chainmail section would replace the passive metal splint. In the actuated state, the chainmail would provide stiffness and support, and in the un-actuated state, the device would afford a greater range of motion to the patient.

ACKNOWLEDGMENTS

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