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Low-cost 3D-printable Prosthetic Foot

Jonathan Yap and Gianni Renda

Swinburne University of Technology, AUS

Abstract

Home 3D printing technology is rapidly evolving from a means of creating low-fidelity trinkets, to becoming a robust and viable method of batch production. This paper explores the potential that this technology has on the manufacture of prosthetic feet for children from developing countries – specifically referring to the variance in sizes as the child grows. An exploration of the design process undertaken in an industrial design honours year demonstrates how a low-cost (approx. AUD$15.00 at wholesale material prices), 3D-printed prosthetic foot has a comparable, if not better, performance level than a SACH foot – the type of foot typically donated to provide aid to those from developing countries who would otherwise be unserved. Prototyping was undertaken using a hobby-level printer (the Makerbot Replicator 2) and Polylactic Acid (PLA) filament. This method of prototyping allowed the designer to undertake rapid iterations of the prototype to undergo basic testing using autoethnographic methods. The prosthesis' ability to be modified and produced on-site, on-demand could potentially redefine the opportunities available to prosthetists for accommodating varying gait patterns when providing low-cost aid to developing countries.

Keywords: Prosthetics, accessibility, user-centred design, low-cost, 3D printing

Introduction

Achieving a more natural gait pattern reduces strain on amputee's residual limb by reducing compensation strategies employed during ambulation (Buckley *et al*, 2013), however the price increase required for improved performance capabilities alienates those who cannot afford the typically high prices of these interventions. While these developments are undeniably beneficial for the amputee population, the cost of these devices cannot be overlooked; a high-end prosthetic foot can retail for as much as $5000 (USD). As such, emphasis must be placed on developing new solutions for those from lower socio-economic areas to fulfil their rights to

> "full and effective participation in society on an equal basis with others" (United Nations, 2006, 'Convention on the Rights of Persons with Disabilities and Optional Protocol', p. 4).

The use of rapid prototyping technologies for medical applications has been rapidly emerging (Šljivić *et al*, 2011), with 3D printing being successfully employed to fabricate transtibial prosthetic sockets, ankle-foot orthoses and prosthetic ankles (Faustini *et al*, 2008; South *et al*, 2010); implying a potential applicability in the fabrication of low-cost, customised prosthetic feet. Lipson (2011) also identifies the ability to fabricate complex structures with little to no additional manufacturing costs as another important advantage of the 3D printing process. A demographic that may benefit from 3D printed assistive devices are those from developing countries; namely children who require regular fittings of new prostheses due to replacements usually being necessary every 6 months (Hussain, 2011). Although donation-based services exist to provide them with free or low-cost prostheses, the ability to source appropriately sized prosthetic feet for everyone that requires assistance is not always possible (H. Tran, personal communication, September 18, 2013).

Method

Due to high-risk ethics constraints, physical prototype testing was conducted via autoethnographic simulations using a testing rig. As there is no standard objective test to evaluate the performance of a prosthetic foot (Sagawa Jr. *et al*, 2011), results from the simulated prototype testing were considered true, however further controlled evaluation is warranted to validate the research findings.

Initial Sketch Concept Ideation

Initial sketch concept ideation was undertaken to develop a solution that incorporated the main principles of energy-storing-and-return (ESR) feet; being form deformation upon 'heel strike', storing energy that would be transferred through the prosthesis and released during the second and third phases of gait. Recognition of some of the trade-offs that exist with ESR feet, primarily aspects pertaining to keel stiffness, prompted a direction that explored the potential of a modular prosthetic foot design; where keel stiffness would be dictated by inserts with different levels of flexibility, allowing foot performance to be altered depending on the activity of the user. This idea developed to incorporate the use of a squash ball within the heel region, with the differing compression characteristics of different ball speeds dictating keel stiffness.

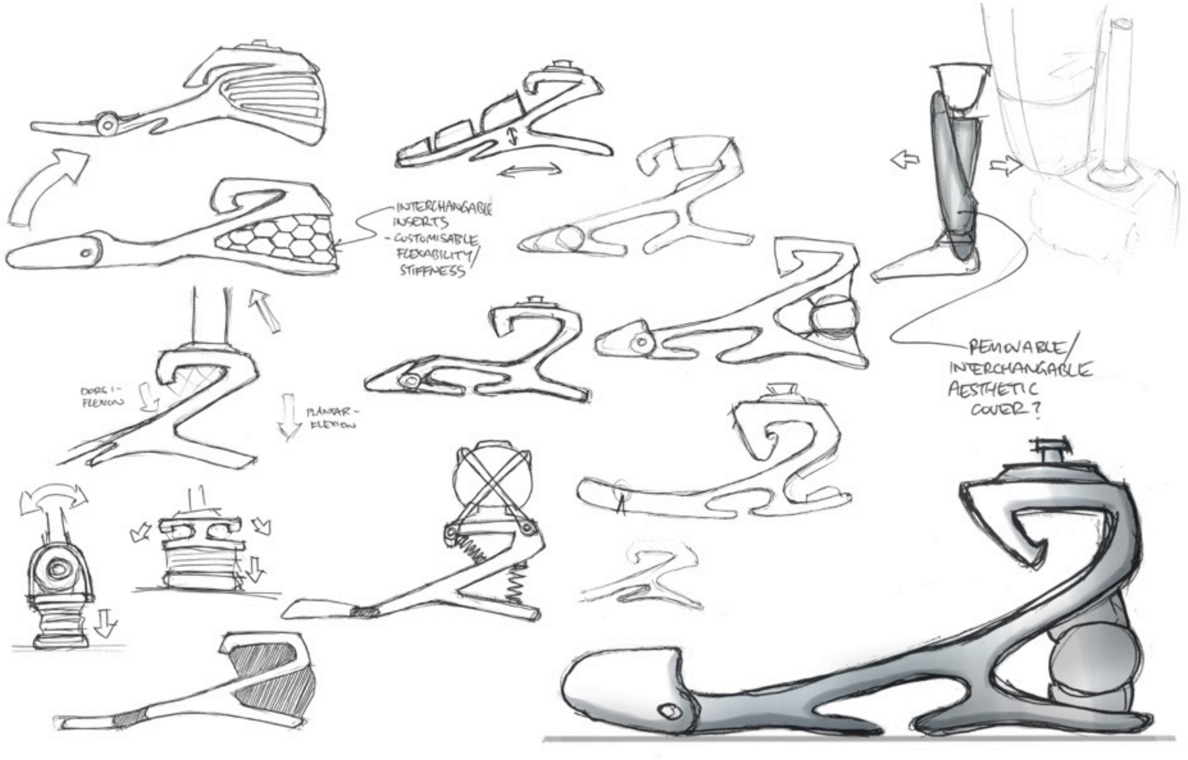

Figure 1: Initial sketch concept ideation

SACH Foot Testing

The SACH (Solid Ankle Cushioned Heel) foot was evaluated using the testing rig for benchmarking purposes. The 75kg subject reported similar drawbacks as those recognised by De Asha *et al* (2013), such as having to

> "'Climb over the prosthetic foot', 'stuttering' and [the] experienc[e of] a 'dead spot' during stance" (p. 218),

as well as identifying overall stability as a key concern. The subject attributed this to the SACH foot being rounded on both the medial and lateral sides, noting that weight had to be accurately placed through the centre of the foot for maximum stability. Additionally, the SACH foot's compliant toe region validated Ertis *et al*'s (2012) findings regarding the requirement of a stiffer toe to sufficiently

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"support the [user] throughout the entire course of the step" (p. 40).

These findings therefore became key design considerations when furthering the development of the initial sketch concepts.

Figure 2: SACH foot testing via an autoethnographic method. The testing rig utilised a snowboard binding to restrict the test subject's ankle movements.

CAD Concepts

Six preliminary CAD models were produced; however ultimately only one concept was taken further. Undulations on the base of the foot were designed to provide stability on uneven terrain; with the four contact points (when plantigrade) spanning the width of the prosthesis ensuring that accidental inversion/eversion due to rounded medial and lateral sides was prevented. Minimising the compliance of the toe region was integral to not only provide a platform to support the user throughout all phases of gait, but to also ensure maximum energy return during the third phase of gait (Ertis *et al*, 2012). The design of the mounting pyramid was inspired by existing designs, permitting up to 7° of swing angle adjustment in two planes, allowing for the alignment of the prosthesis for users with differing gait mechanics.

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Figure 3: CAD Concepts

While the profile of the design remained constant, the various CAD models explored the idea of incorporating and/or not incorporating hexagonal compressible structures to provide increased energy return, as well as the exploration of the inclusion and/or exclusion of a squash ball, as its effect on keel strength was still to be established. Additionally, variations also explored the reduction of material through the mid-foot to promote greater flex through this region. Ultimately, the chosen concept taken through to prototyping incorporated the squash ball within the heel region and the reduction of material through the mid-foot, as it was believed that full-scale prototyping would reveal whether the conceived compressible structures would have any impact on performance, and if so, could be added later.

1:4 Scale Test Prints

1:4 scale prototypes were printed to test how the Makerbot Replicator 2 would print the complex form of the concept chosen. It was apparent that printing of the prototypes required supports and rafts, the latter ensuring better print adhesion to the build platform. Three 1:4 scale prototypes were printed at different orientations to observe how the Makerbot would print the support material and it was decided that the 1:1 scale prototypes would be printed on its side, with the medial side of the prosthesis facing downwards; closest to the build platform. This decision was made due to two major factors: a) the ease of removing the support material and b) part strength. Like wood grain, the 3D printed component was much stronger across the layers than along, and therefore it was imperative that the layers ran along the length of the prosthesis in order to not only be able to withstand stress and impact loads, but to also allow for flex along the length of the form.

Full Scale V1

Production

The first full-scale prototype was achieved with print settings of 6 passes with a 50% hexagonal infill pattern. The build took 24 hours 27 minutes to complete and consumed 354g of PLA, inclusive of rafts and support material; which was equivalent to $8.12 at wholesale material prices. The rafts and support material were removed, with the excess being sanded back. As part failure was anticipated, exterior surface strengthening was conducted by applying 2-part epoxy around the mid-foot and the mounting mechanism, which was sanded after curing to achieve a smooth surface finish. To address PLA's potential susceptibility to water, the prototype was coated with a multi-purpose synthetic rubber, with a layer of pumice (crystalline silica) grit being added to the base to increase the rubber's non-skid properties. After prototype finishing was completed, and the squash ball inserted, the prosthetic foot weighed 340g; 22g lighter than the SACH foot previously tested.

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Figure 4: Full scale prototype V1

Evaluation

The prototype was evaluated using the testing rig and was recorded on a Canon EOS 7D. Not only was the prototype was able to support the subject's weight (75kg), but drastic performance improvements over the SACH foot were experienced; such as improved comfort and energy return, as well as increased overall stability. Furthermore, it was also noted that the 'stuttering' and the 'dead spot' was not present during testing of the printed prototype, and that the decrease in weight allowed for easier, more natural ambulation. However, the subject identified that the inclusion of the squash ball made little-to-no difference to keel flexibility as the foot performed similarly when it was removed. After repeated testing, the mounting pyramid eventually broke, indicating that reinforcement was necessary. Additionally, the prototype was fitted with various types of footwear, all of which implied form suitability.

Analysis of the recorded testing provided further insights into the functionality of the prototype, with the design dynamically directing and dispersing the impact and transferring loads admirably. Slight compression occurs upon heel strike simulating a degree of plantarflexion, albeit not significantly enough for the squash ball to have any influence upon function, and the curve of the heel design promotes a natural roll over until the prosthesis becomes plantigrade; with its four contact points providing stability and dispersion of some of the impact load. Furthermore, as the contact points span the width of the prosthesis, accidental simulation of inversion/eversion due to rounded medial and lateral sides was prevented, thus providing evidence for its stability superiority over the SACH foot. As weight is transferred past the instance when the shank is perpendicular to the ground, the upper portion of the prosthesis flexes forwards, storing energy until it reaches its maximum 10° of simulated dorsiflexion. Simultaneously, the mid-foot flexes and also stores energy until 'heel-off', when resiling of the upper region occurs followed by the mid-foot, thus providing energy return through the second and third phases of gait. Analysis of the prototype's functionality further validates discontinued exploration of the other CAD models previously produced, as the effect that their features would have had on performance would be negligible.

Further Design Development

The demonstrated functionality of the first full-scale prototype suggested that most of the design features should remain unchanged, however, developments pertaining to reinforcements and squash ball utilisation were made. As the overall form of the foot performed admirably, minimal changes were made apart from a 1.5mm thickening of the mid-foot region to allow for metal rods to be embedded. Although the first prototype did not break through this region, the addition of reinforcement through this section was deemed necessary to increase confidence in the structural integrity of this area. It was decided that the squash ball was to be removed entirely due to its inappropriate elastic properties; which would also further reduce material consumption. Allowances were also made to enable a ¼" threaded steel rod to be embedded within the mounting pyramid for increased structural support. Additionally, a grip design was debossed into the base of the prosthesis to increase non-skid properties.

Full Scale V2

Production

The second full-scale prototype was achieved with print settings of 6 passes with a 30% hexagonal infill pattern in order to further reduce material consumption. The build took 20 hours 49 minutes to complete and consumed 322g of PLA, inclusive of rafts and support material, which was equivalent to $7.38 at wholesale material prices. The rafts and support material were removed, with the excess sanded back. A ¼" threaded steel rod was then bent, cut and hammered into place with a rubber mallet; and then secured with 2-part epoxy which was sanded after curing to achieve a smooth surface finish. The prototype was finished with a synthetic rubber coat and a layer of pumice grit added on its base for increased non-skid properties. Following prototype finishing, the prosthetic foot weighed 334g.

Figure 5: Full scale prototype V2

Evaluation

As expected, the prototype performed to the same standard as the first iteration. Reinforcement appeared to be sufficient, as the prototype retained its strength for the entire duration of testing. The reinforced mounting pyramid was also able to sufficiently cope with lateral forces exerted on it, suggesting that light levels of recreational sport (soccer) may be achievable with the prosthesis. While testing confirmed the framework presented for a dynamic, weight bearing structure primarily produced with FDM PLA, further evaluation with transtibial amputees and controlled fatigue testing is warranted to validate the research findings.

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Discussion and Conclusion

The solution presents the framework for a dynamic, weight-bearing structure that is primarily produced with FDM PLA, with ¼" threaded rods embedded to increase the structural strength properties of the prosthesis. The prosthetic foot's dynamic energy-storage-and-release capabilities ensure a higher level of comfort when ambulating when compared to the SACH foot (the type of prosthesis that would typically be donated to developing countries). The prosthetic foot presented offers up to 3° of simulated plantarflexion upon 'heel strike', depending on the user's weight, with the curved design of the heel providing a natural rollover until the prosthesis is plantigrade. Additionally, a maximum of 10° of simulated dorsiflexion can be achieved, allowing for stance modification when stationary, as well as allowing for easier ambulation, due to its energy-storage-and-return capabilities. When plantigrade, the four contact points that span the width of the prosthesis allows for superior stability, preventing accidental simulation of inversion/eversion due to rounded medial and lateral sides, with the undulations of the base allowing for stability to be achieved on uneven terrain. The compliance of the mid-foot also allows for energy storage during gait, with the less compliant forefoot providing a platform to not only support the user throughout all phases of gait, but to also ensure maximum energy return during the third phase of gait (or 'toe off'). Additionally, the mounting mechanism, which attaches to the prosthetic shank by two pairs of setscrews surrounding the pyramid, permits up to 7° of swing angle adjustment in two planes, allowing for the alignment of the prosthesis for users with differing gait mechanics. Using standard footwear with the prosthesis would decrease the wear of the synthetic rubber coating, provided to protect the printed PLA from the elements, and thus extend its lifespan.

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