Viability of Distributed Manufacturing of Bicycle Components with 3-D Printing: CEN Standardised Polylactic Acid Pedal Testing

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ABSTRACT: *Recent advancements in open source self-replicating rapid prototypers (RepRap) have radically reduced costs of 3-D printing. The cost of additive manufacturing enables distributed manufacturing of open source appropriate technologies (OSAT) to assist in sustainable development. In order to investigate this potential, this study explores the use of RepRap 3-D printers to fabricate widely used Black Mamba pedals in the developing world. A CAD model of the pedal was created using parametric open source software (FreeCAD) to enable future customisation. Then polylactic acid, a biodegradable and recyclable bioplastic, was selected among the various commercial 3-D printable materials, based on strength and cost. The pedal was tested following the CEN (European Committee for Standardisation) standards for racing bicycles for static strength, impact, and dynamic durability. The results show the pedals meet the CEN standards and can be used on bicycles. The 3-D printed pedals are significantly lighter than the stock pedals used on the Black Mamba, which provides a performance enhancement, while reducing the cost of raw PLA or using recycled materials, which assists in reducing bicycle costs. For a return on investment, other bicycle parts could also be manufactured using 3-D printers, hence this model of distributed manufacturing of OSAT may be technically and economically appropriate through much of the Global South.*

KEYWORDS: 3-D Printing, Bicycle, Distributed Manufacturing, Mechanical Properties, PLA, RepRap

1 INTRODUCTION

Recent advances in additive manufacturing and 3-D printing have been forecast to bring on the next industrial revolution (Berman, 2012; Rifkin, 2014). With the technological evolution of the self-replicating rapid prototyper (RepRap), an open source 3-D printer that can fabricate more than half of its own parts (Sells et al., 2010; Jones et al., 2011; Bowyer, 2014), the costs of 3-D printers have fallen from tens of thousands to a few hundred dollars. Already RepRap printer designs make up the majority of 3-D printers in use (Moilanen and Vadén, 2013). This allows for the radical rearrangement of production (Rundle, 2014; Rumpala, 2016) to follow peer-to-peer methods (Moilanen, 2012; Moilanen and Vadén, 2013; Troxler, 2010) and even for consumers to become "prosumers" and make their own products (Mota, 2011; Anzalone et al., 2015; Laplume et al., 2016). A study has already shown that ownership of a RepRap 3-D printer is economically beneficial for American consumers if it is used to fabricate a modest number of products in a year, offsetting conventional purchases thanks to the rapid expansion of free and open source designs for products on the Internet (Wittbrodt et al., 2013). In addition, this form of distributed manufacturing has an environmental benefit due to the decrease in shipping and often less intensive additive manufacturing (Kreiger and Pearce, 2013a; b).

3-D printing has been touted as democratising manufacturing in the developed world. There have also been proposals to use 3-D printing for sustainable development in marginalised communities (Pearce et al., 2010; Canessa et al. 2013; Lopes da Silva, 2013). The application of 3-D printers in the developing world has enabled the manufacturing of necessities in the field following a humanitarian crisis by groups such as Field Ready (Field Ready, 2016). 3-D printers can also be used directly for development in the developing world (Birtchnell and Hoyle, 2014); this can be done by recycling thermoplastic post-consumer waste into 3-D printing filament using recyclebots (waste plastic extruders) (Baechler et al., 2013; Feeley et al., 2014; Cruz et al., 2015; Hamod, 2015; Hunt et al., 2015). 3-D printers can be used to fabricate appropriate technology, encompassing small-scale, decentralised, labour-intensive, energy-efficient, environmentally sound, and locally controlled technologies (Hazeltine and Bull, 1998). Appropriate technology can be developed using open source principles, which have led to open source appropriate technology (OSAT) (Pearce, 2012) and thus plans of many technologies to be found freely on the Internet (Louie, 2011; Pearce, 2012).

In order to investigate the potential of distributed manufacturing of OSAT this study makes a careful investigation of the use of RepRap 3-D printers to fabricate widely used bicycle components in the developing world.

Bicycles serve as a primary form of transportation for people throughout much of the developing world. Greater access to working bicycles can also provide long-term benefits to developing communities by giving people an expanded range of travel, and enabling increased access to health care, markets, and education. Bicycles are used not only for personal transportation, but also for the transporting of goods and materials making the bicycle a tool for agriculture, commerce, and general economic empowerment.

Specifically, this study tests pedals fabricated using polylactic acid (PLA), a biodegradable and recyclable bioplastic. First, a CAD model of the pedal was created. Then the material was selected among the various commercial materials based on strength and cost. Then the pedal was 3-D printed on a commercial RepRap and tested following the CEN (European Committee for Standardisation) (European Committee for Standardisation 2005) standards for racing bicycles with static strength testing, impact testing, and dynamic durability testing. The results are presented and discussed in the context of distributed manufacturing of OSAT in the developing world.

2 METHODS

The methodology included first selecting amongst various commercial materials, based on strength and cost, then developing an open source design using only open source tools, and describing the open source 3-D printer used, along with the settings to fabricate the pedal. Then the tests for the pedal performance were designed to meet or exceed the CEN standards. The European racing bicycle standard CEN 14781 (European Committee for Standardisation 2005) was chosen to provide performance results, which would be most convincing to the target audience.

2.1 Material Selection

In the RepRap community PLA is the most popular 3-D printing material, being available for the majority of 3-D printing supplies vendors. PLA has a relatively low melting point (150°C to 160° C) requiring less energy to print than many alternatives, a distinct advantage for off-grid applications in the developing world (King et al., 2014; Gwamuri et al., 2016). In addition, PLA has been shown to be a safer alternative to toxic ABS plastic fumes, the second most widely available 3-D printing material (Groenendyk and Gallant, 2013; Merlo et al., 2015).

The mechanical properties of RepRap 3-D printing materials have therefore been investigated in some detail (Tymrak et al., 2014; Wittbrodt and Pearce, 2015; Tanikella, 2016). The strength of the printed specimens and the costs of various commercial materials (Aleph Objects Incorporated, 2016) are compared in Table 1. As can be seen in Table 1, PLA has the highest strength to cost ratio and was chosen for this study.

2.2 Open Source Design

The pedal was designed for ease of printing (e.g., minimising overhangs) and least number of parts. It was designed using an open source CAD software (FreeCAD, 2016). The bicycle pedal was designed using the dimension of the spindle for the stock 100 mm x 77 mm

Table 1: Comparison of strength, cost of various commercially available materials

Material	**Cost of the Filament Tested ($USD/kg)**	**Average Maximum Tensile Stress (MPa)**	**Standard Deviation of Maximum Tensile Stress (MPa)**	**Strength to Cost Ratio (MPa. kg/$USD)**	**Reference**
ABS	42.95	28.75	3.15	0.67	(Tanikella, 2016)
ABS	42.95	28.5	n.a.	0.66	(Tymrak, 2014)
HIPS	24.95	20.71	1.27	0.83	(Tanikella, 2016)
Nylon 618	43.50	31.60	3.20	0.72	(Tanikella, 2016)
Polycarbonate	74.95	49.08	3.03	0.65	(Tanikella, 2016)
T-Glase	66.00	32.55	4.21	0.49	(Tanikella, 2016)
PLA	24.95	53.77	1.46	2.16	(Wittbrodt and Pearce, 2015)
PLA	24.95	56.6	n.a.	2.27	(Tymrak, 2014)

pedal of the Black Mamba bicycle (Baisikeli Ugunduzi, 2016) as a reference. The Black Mamba is the East African common name for the most popular bicycle in the developing world; however, its pedal can be used on other spindles with slight modifications to the parametric design.

The top, side, front, and axonometric views of the design pedal are shown in Figure 1. The geometry chosen suits the spindle, bearings and bearings holder; this differs to the Black Mamba in design in order to make it lighter for the required strength. Whilst the stock pedal is removable, with four plastic parts and two other metal parts, the 3-D printed pedal is a single piece.

2.3 RepRap 3-D printer

The Taz 4, a commercial open source version of the RepRap 3-D printer, was utilised for the design process (Aleph Objects Incorporated, 2016), (Aleph Objects, 2016) at a cost of USD $2,200. The print area is 290 mm x 275 mm x 250 mm, designed for a 3 mm diameter filament and includes a heated bed for better adhesion and dual extruders. The pedal design only requires 80 mm x 30 mm x 116 mm, hence, less expensive 3-D printers with smaller print areas and can be utilised. It should be noted that less expensive printers often do not have a heated bed as in the case here, however, previous testing has shown that cold-bed 3-D printing on RepRap printers is capable of producing parts with identical and even superior properties to commercial 3-D printers with the same materials, even in heated chambers (Tymrak et al., 2014).

2.4 Print Settings

The Cura 15.04 (Ultimaker, 2017) was used as a slicer for generating Gcode from the CAD model. Other research has described what effect the orientation of layers may have on the properties of a printed part (Vega et al., 2011) and commercial grade fused deposition modelling (FDM [the intellectual property limited subset of fused filament fabrication (FFF), which can only be used by the trademarked owner]) printers have shown a strength dependency on different types of infill patterns and internal structures (Rosas, 2013). The pedal was printed at 50% infill (cubic grid) with 1 mm thick solid outer shell. A 100% infill would have increased the weight of the pedal beyond feasibility but a solid outer shell helps retain the shape during printing and also helps absorb impact energy. The mass of the pedal was estimated to be 111 g (118 g including the supports for printing) and printed using the Lulzbot Taz 4 printer; the final actual mass of the pedal was 104.44 g. The print time was 6 hours and 18 minutes.

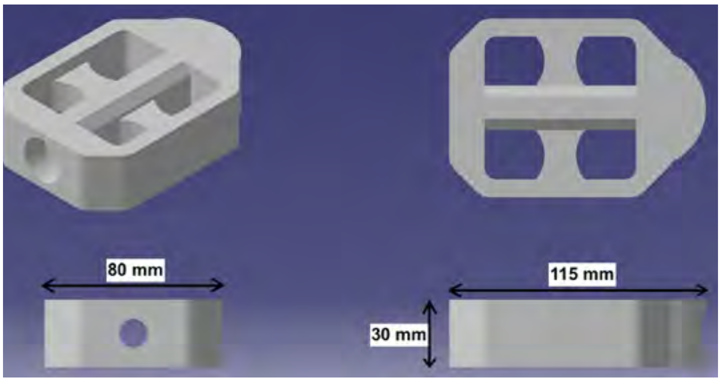
2.5 CEN Testing

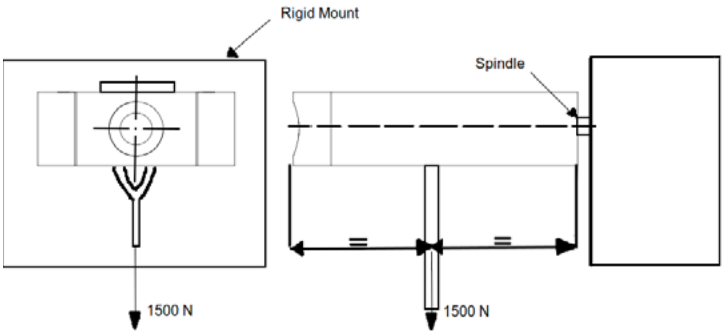
The CEN standards for pedals require the passing of three different tests: static strength, impact, and dynamic durability.

2.5.1 Static strength test

The CEN static strength test for bicycle pedals requires that the pedal be subjected to a 1500 N vertical downward force as shown in Figure 2. The test is satisfied if there are no fractures present.

The pedal was tested on a Universal Testing Machine with setup shown in Figure 3; the testing equipment was an Instron 4206. Compression load of 3,000 N was applied uniformly on the pedal, double the prescribed amount to clearly test for exceeding the standard. The load is applied by the hydraulic system by compressing the crankshaft-pedal-spindle setup. The setup also includes a rigid iron grip and a load cell.





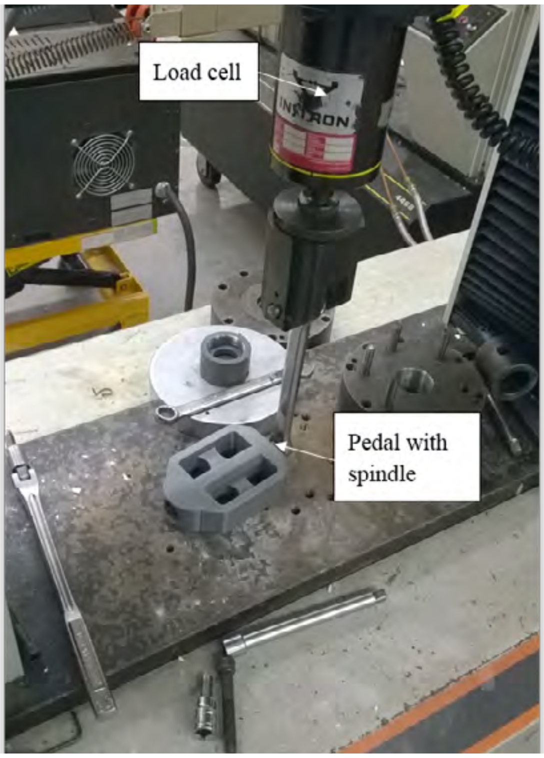


Figure 1 (top left): Open source 3-D printable bicycle pedal

Figure 2 (bottom left): CEN static strength test method schematic

Figure 3 (right): Test setup on a Universal Testing Machine

2.5.2 Impact test

The CEN impact test for bicycle pedals requires that a mass of 15 kg be dropped on the pedal from a height of 400 mm, 60 mm from the mounting face, as shown in Figure 4. The test is satisfied if there are no fractures or permanent sets beyond 15 mm.

A small aluminium rod of radius 3 mm and 20 mm in length was stuck on the pedal at 60 mm from the mounting face using super glue. The aluminium rod is solid and was attached on the pedal. It was attached as a replacement for the striker, as per the radius and length requirements. The glue did break after the impact, but it stayed in place. The mass assembly (Figure 5-a) was dropped on the pedal with the help of the rigid guide assembly fixture (Figure 5-b). The rigid fixture is an aluminium frame. The two rubber pieces hold the pedal in place whilst the mass is dropped onto the pedal for impact. The mass consists of three 4.54 kg masses along with approximately 2 kg of the aluminium assembly, totalling slightly over 15 kg.

2.5.3 Dynamic durability test

The CEN dynamic durability test for bicycle pedals requires that the spindle be spun at 100 rev/min for a total of 100,000 revolutions. The pedal should have a mass of 65 kg suspended by a spring. This test is intended to simulate a real-world bicycle with a person standing on the pedals. The test is satisfied if there are no fractures or cracks in the pedal-spindle system.

In this case, testing was designed to surpass the CEN standard in more realistic conditions. The pedal was attached to a bicycle and tested directly rather than with a testing rig. The pedal was tested for about 300,000 revolutions (50 hours over a period of 2 weeks), with approximately 200,000 revolutions where the person's weight was carried by the pedals alone. This is double the number of CEN standard revolutions. The weight of the person was 75 kg. The cadence fluctuated between 90 and 100 rpm for most of the test duration.

3 RESULTS

We conducted three CEN pedal tests for the 3-D printed pedal: static strength testing, impact testing and dynamic durability testing. Overall, the CEN pedal tests of the 3-D printed pedal were successful.

3.1 Static strength test

Upon completion of the CEN static strength test on the bicycle pedal, no fractures, visible cracks, or distortion of the assembly were observed.

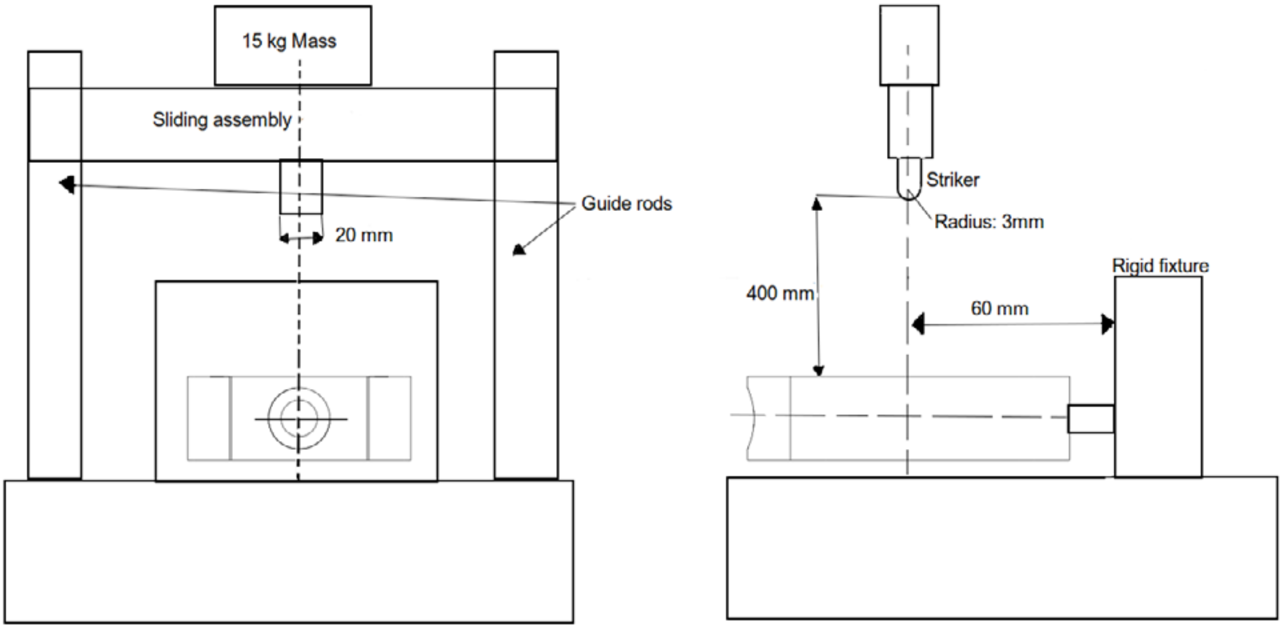


Figure 4: CEN impact test method schematic

3.2 Impact test

Upon completion of the CEN impact test on the bicycle pedal, no fractures were observed. A small visible "dent" less than 1 mm deep was observed at the impact point, as can be seen in Figure 6.

3.3 Dynamic durability test

Upon completion of the CEN dynamic durability test on the bicycle pedal, no fractures or visible cracking were observed on the pedal.

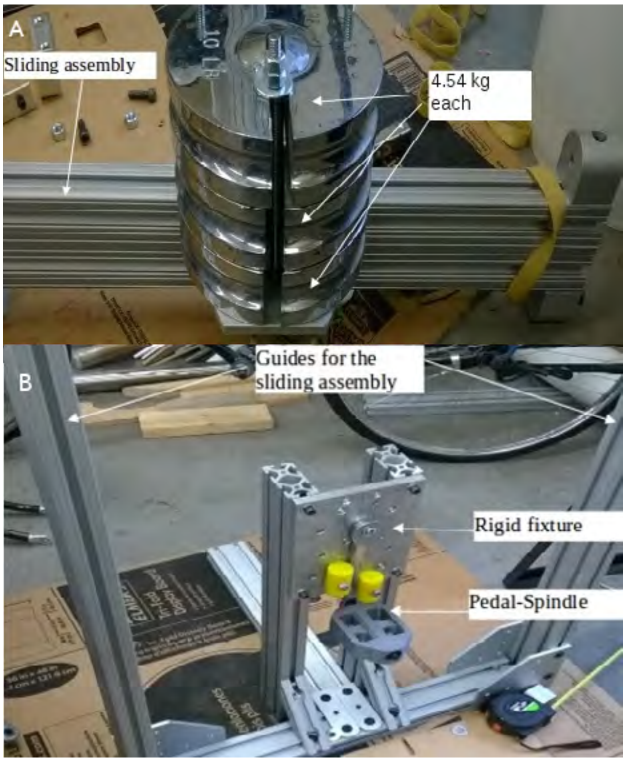
4 DISCUSSION

The stock Black Mamba pedal costs 280 Kenyan Shillings (KES) in Kenya, which is equivalent to USD $2.77. This includes the spindle and bearings that have not been printed, due to the high strength required by the spindle and difficulty in manufacturing the bearings.

Upon pedal failure, the bearing and spindle are likely reusable, as pedals used on the typical Black Mamba bicycle have two plastic pieces that are held to the axle with two thin-stamped plates to which they are screwed at their ends. It does not take long for these plastic pieces to wear and then they eventually come loose from the endplates that hold them to the spindle. At this point, these components become a hindrance to pedalling and are removed, leaving only the steel spindle. Unlike steel pedals or high quality plastic pedals used in the developed world, these plastic sides fail much more quickly than the bearings. The bearings are also easily maintained by local mechanics, as they are not sealed. The stock pedal weighs 277 g (excluding the spindle and bearings). The 3-D printed pedal is intended to be a replacement for the stock pedal, used with the bicycle's original spindle and bearings. The 3-D printed pedal is not a direct replacement for the entire pedal assembly (pedal, spindle and bearings). A comparison of the cost of material for the 104 g tested pedal is shown in Table 2.

It should be noted that in Table 2 labour costs were excluded in all the systems to enable a direct comparison. Labour time would be more extensive for the recyclebot cases. Although the labour time would be the same for any shop in a given process, the cost of that labour would be highly variable ranging from free labour from employees on site who were able to process in between other activities, to full time employment for equipment operators).

As can be seen in Table 2, commercial PLA from proprietary vendors produces a pedal that is more than double the cost of the stock pedal (which also includes the bearings and spindle). For pedals that fail, this cost can be directly compared as the spindle and bearings would be re-used. PLA from open source vendors is about 5% more expensive than the stock pedal; this cost differential could be easily overcome by further refinement of design, but it is clear that the costs of the stock Black Mamba pedals are well below even the cheapest pedals sold in developed economies (e.g., the least expensive pedals in the US market ranges to from USD $4.99 to $30.00 based Google Shopping 06/10/2016).



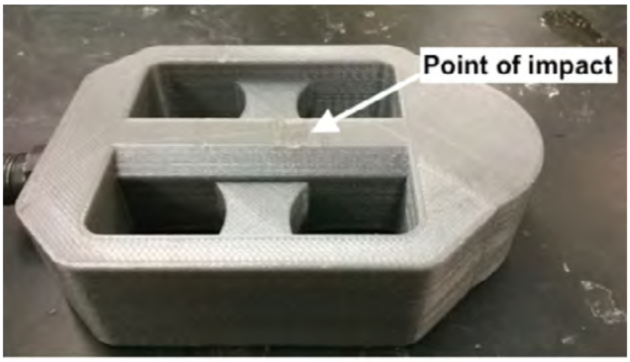


Figure 5 (top): Impact test setup

Figure 6 (bottom): Pedal after the impact test

Filament however is still sold at a substantial mark-up, as raw pellets can be purchased for under USD $5.00 per kg, reducing the cost of the 3-D printed pedal by a factor of five and ten compared to the open source and proprietary filament vendors, respectively. Bicycle shops or other small companies, or even individuals, can purchase a commercial recyclebot (e.g., Filastruder) or build one from freely available plans to produce their own filament. Doing so would drop the price of a printed pedal to nearly one-fifth of the current cost of the Black Mamba pedal.

If waste plastic can be procured (e.g., spent PLA food containers) the price of the pedals can fall to USD $0.01 for the materials cost. PLA is used in only select applications now, but it is becoming a more popular polymer to be used in packaging of all kinds (e.g. Wal-Mart containers). In some locations where there are no sources of PLA waste, other polymers may potentially be used in recyclebots and RepRaps, but this would require further testing in future work.

The development of 3-D print shops have been proposed in the industrialised world as distributed manufacturing offers a large potential profit from reduced manufacturing costs (Laplume, Anzalone, & Pearce, 2016). It is useful to analyse the potential for such 3-D print shops (perhaps located within a more conventional bicycle shop) in the developing world.

If it is assumed that the parts for RepRap and recyclebot can be purchased for USD $1,000 (based on the initial published costs of a RepRap and recyclebot (Appropedia, 2016; Irwin, et al., 2015), then 1,010 pedals could be manufactured at a materials and equipment cost of USD $1.00 per pedal

As the print time is over 6 hours per pedal, it can be assumed that a print start occurs once at the start of day and once at the end of day, resulting in 505 days of printing. Thus, even for this extremely low-cost part, the payback time is less than 1.5 years. As commercial pedals sell for USD $2.77, there is substantial potential revenue to account for labour and expenses as well as a potential healthy profit.

Realistically, the recyclebot and RepRap distributed manufacturing system would be used to fabricate far more than a single low-cost product. Other potential products are: replacement parts for small local bicycle retailers, agricultural implements, water pumps, medical and scientific equipment and homeware (Canessa et al., 2013; Pearce, 2013; Wijnen, et al., 2014), (Pearce, 2015b), and (Wittbrodt, et al., 2013).

The biggest advantage of this pedal, and the distributed manufacturing approach, is that the pedal can be printed in remote locations. In remote and rural areas, bicycles may be the reliable form of transport, subjected to the harshest conditions and access to spare parts is necessary, but expensive. Supply chains servicing rural and remote areas may not be able to adequately keep bicycle parts stocked sufficiently at affordable prices. Typical items stocked are expensive at wholesale, which can make it difficult for small or rural retailers to sufficiently profit from their sale.

The printed pedal is significantly lighter than the stock pedal (104 g vs. 277 g) and would provide some energy efficiency over the standard pedal. Future work is needed to determine if the pedal would be acceptable to consumers.

The pedal is accessible to anyone with a basic FFF 3-D printer, basic computer skills and sufficient filament; this allows local bicycle shops in the developing world to print

Table 2: Cost of the pedal based on material source

PLA material source	Cost per kg (USD $)	Pedal cost (USD $)	Reference
Commercial PLA closed source	53.33	6.30	(MakerBot® Industries, 2016)
Commercial PLA	24.95	2.90	(Aleph Objects Incorporated, 2016)
(PLA pellets through recyclebot)	<5.00	0.59	(NatureWorks LLC, 2016
Recycled PLA via recyclebot	~0.10	0.01	Kreiger et al., 2014)

pedals, instead of relying on supplied stock. In addition, a 3-D print shop may offer the pedal as one of many varied products, which would save on transportation costs and storage costs as the products do not have to be kept in stock at all times. The local bicycle shops or 3-D print shops can modify the design easily, enabling scope for customisation to suit the needs of the community, or to provide higher value products to consumers. Consumers can also print the pedal at home, using desktop 3-D printers. This would be economical as well as convenient.

5 CONCLUSIONS AND RECOMMENDATIONS

Replacement pedals for a typical developing world bicycle were successfully designed using open source software and manufactured using an open source 3-D printer. These pedals were tested following the CEN bicycle pedal standards and the results show that the pedals meet the standards and can be used on bicycles.

The 3-D printed pedals are significantly lighter than the stock pedals used on the Black Mamba, which provides a potential performance enhancement. The pedals can be made using recycled materials, reducing material costs, to enable access for those living in poverty.

The pedals are customisable and can be easily drafted by anyone with basic CAD program training. CAD drawing files can be made locally, or downloaded from a freely accessible online database. 3-D printing can also allow for the manufacture of various bicycle parts by bicycle shops, which can increase return on investment in a 3-D printer

There are many materials available on the market for prosumer FFF 3-D printing. A recent study has already investigated the mechanical properties of RepRap 3-D printed parts using a commercial open source RepRap for a wide range of materials. Future work could probe the use of these other materials for bicycle components. With the continued development of novel and affordable 3-D printing technologies, the types of materials that may become common for FFF is expected to grow (Pham and Gault, 1998; Yan and Gu, 1996) and involve the use of additives (Pearce, 2015a) such as strengthening agents to common 3-D printable materials (Torrado Perez et al., 2014; Compton and Lewis, 2014) or treating 3-D printable materials to increase strength (Shaffer et al., 2014). In addition, other components of the bicycle such as handlebars, brake levers, brake pads, handlebar grips, etc., could be designed and tested.

Although the tensile strength of many 3-D printing materials are available, these results cannot be used for structural analysis directly. The orientation, infill density, direction of force applied, type of forces, etc. change the strength of the component being analysed. A database of mechanical properties for various combinations of orientations, infill density, and direction or method of forces applied would enable FEA analysis of components that would allow better designs and reduce testing time.

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