Performance benefits of sports equipment produced using rapid prototyping techniques

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INTRODUCTION
Rapid prototyping has the potential to make impossibilities through other manufacturing techniques, possible. Rapid prototyping is becoming increasingly more popular within a variety of industries, and the branching out in to the sports industry could revolutionise some sports like never before. As said in “Additive Manufacturing: Going Mainstream”, Rapid prototyping is “poised to someday become one of the most valued forms of manufacturing ever” (Caffrey, T and Wohlers, T; 2013). The huge number of possibilities enabled from this technology could revolutionise manufacturing for the future. The reasoning behind the research in to this subject is to explore how Rapid prototyping is involved with industry currently, and how it could develop to become a larger influence within sport.

1. Aim of this Study
The aim of this project is to evaluate how 3D printing techniques can affect athlete’s performances when applied to the design of sports equipment, through looking at how rapid prototyping is used within sport.

PERFORMANCE BENEFITS OF SPORTS EQUIPMENT PRODUCED USING RAPID PROTOTYPING TECHNIQUES

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ABSTRACT
Rapid prototyping is an advancing technology that allows the manufacture of parts through layering material, unlike conventional methods of manufacture that typically removes material. The process is becoming more and more popular within different industries because of the capabilities that it can provide; there are also many applications of this process that can create improved products from how they were originally manufactured. The aim of this project is to evaluate how 3D printing techniques can affect athlete’s performances when applied to the design of sports equipment, through looking at how rapid prototyping is used within sport. Interviews with athletes that have experience using 3D printed sports equipment would prove very useful to his project, however, the arrangement of this interview may prove difficult. Further investigation and review of current and proposed rapid prototyping projects will also be another research method used through this project.

Keywords- Rapid Prototyping, Sports Equipment Design.

2. Objectives and Research Questions
The specific area objectives and the related research questions are:

- To examine rapid prototyping techniques applied to sports equipment.
1. What variations of rapid prototyping have been used within sport?
2. How do products produced through rapid prototyping vary from similar products produced using other methods?
3. How is rapid prototyping going to change sporting equipment in the future?
4. What is beneficial about using the rapid prototyping manufacturing process?
5. How can the rapid prototyping sports equipment aid with benefitting athlete’s performances?

- To investigate how sporting equipment has changed with the introduction of rapid prototyping.

Keywords- Rapid Prototyping, Sports Equipment Design.
1. What has changed with sporting equipment since the introduction of rapid prototyping?
2. How is rapid prototyping going to change sporting equipment in the future?
3. How has equipment not produced through rapid prototyping changed since its introduction to sport?

The review and evaluation of these areas of question should outline the effectiveness of the rapid prototyping process within sport; through summarising the results and efficiency of the equipment produced.

3. Literature Review

This section explores the use of 3D printing within sporting scenarios through looking at sport specific case studies, what 3D printed products have been produced and how the authors portray the effects of these products. The articles on these case studies provide varied examples of how rapid prototyping has been used, and mixed opinions on the implications of the process. Literature about rapid prototyping as a whole is also included within this review to gather more views on the process and its implications.

There are many opinions on the applications of 3D printing, which vary from experiences with the process; in order to evaluate the effectiveness of the process, it is vital to critique these opinions. A statement about rapid prototyping in general from "Fabricated – The New World of 3D Printing" explains how the use of the process can bring both good and bad aspects; “Yet, technologies are only as good as the people using them” (Lipson, H and Kurman, M; 2013). The technology is there to be exploited for life changing uses, and it is up to those who utilize the technology to create these uses.

From an early review of the available literature related to the possibilities of 3D printing, one of the most important factors of 3D printing is the capability of creating something that would have been impossible to do so otherwise. The manufacturing of product with necessary internal passageways, undercuts and other features could be “impossible to manufacture with conventional techniques” (Bogue; 2013). These exampled features are made possible through this method of manufacture as material is layered up to create a part, rather than material being removed to manufacture the part (EPSRC, 2012).

A related research into the various types of rapid prototyping evaluated the advantages and disadvantages of each one, and can give a good overview of the processes. One of the advantages of the processes in general is, that a variety of materials can be used for most of the processes available. The disadvantages of rapid prototyping as shown within this research are; that parts can warp significantly depending on the geometry, which can alter the function of the part; and some of the processes will require the use of support material of certain parts; these must be removed after completion and can leave a rough surface finish (Fletcher, R and Upcraft, S; 2003). These are just a few personalities of 3D printing that have been noticed through the use of manufacturing process; but do show some of the realistic effects that come with the advanced technology.

A specific example of how rapid prototyping has been used to enhance an athlete's performance is the use of laser sintering to manufacture a personalised titanium handlebar for Sir Bradley Wiggins (Figure 1). This manufacturing method was chosen as it allowed the capabilities to create personalised geometry around its body size and cycling style. D O'Connor, described the finished product as "super lightweight, aerodynamic handlebars" (O'Connor, D; 2015). A quote within the article from James Hunt, a research associate involved within the project implied that, this manufacturing technique made

Figure 1. Sir Bradley Wiggins 3D Printed Custom Handlebars
the shapes created possible, by allowing the design to ‘manage the airflow’ and ‘that would be hard to achieve using other manufacturing techniques’ (O’Connor, D; 2015).

In a similar article on this project, Simon the author, stated that, “If the slight modifications to the handlebars were not necessary leading up to the record attempt, it would have made sense to create the handlebars out of carbon fibre” (Simon, 2015). This shows that, their opinion on the effectiveness of this 3D printed product is that the outcome was unachievable without it. A possible direct result of this production could have been that Sir Bradley Wiggins was able to beat the world record for the furthest distance, that a rider can cycle within one hour, the “Hour Record”, by nearly two kilometres travelling 54.526 kilometres (Cycling Weekly, 2015) their positive thoughts towards the possibilities of rapid prototyping, however these are opinions on the effectiveness of the product and not defining facts.

A similar rapid prototyping technology was also used at a worldwide competition level with in the 2012 Paralympic games, through manufacturing seats for the use in wheelchair basketball. The seats were all individually customised for the athletes so that they are optimised for their body shape and movement (Figure 2). Dr Gavin Williams, who led this project, stated that, this product “represents a huge improvement in a player’s ability” (EPRSC, 2012). This personalised product was only made available to eight players during the 2012 Paralympics, one of which was Ade Orogbemi, who competed as part of the Great Britain Paralympic team (Wrenn, E; 2012). The Paralympic athlete stated that, “The new seat has improved my game enormously”, which shows that, he is pleased with the personalised seat and what has been achieved through using it (Wrenn, E; 2012). The Great Britain wheelchair basktet ball team managed to reach fourth position in the 2012 Paralympics, which is an admirable accomplishment and could have been due to the impact from the advanced equipment used (Paralympic.org.uk, 2012).

The capability of giving an unjust edge to an athlete’s performance is one impression given from the author of another article regarding additive manufacture within Paralympic sport; stating that “Additive manufacture has the potential to give what might be deemed an unfair advantage for some athletes” (Newman, J; 2012). In particular, those with larger expense accounts will have the availability of these customised products. This does not just expand on how the manufacturing process can potentially improve performance, but also how it could also hinder other athletes’ performances without the access to it, through being “an unfair advantage” (Newman, J; 2012).

An interesting application of 3D printing is Hydra-Guard (Figure 3), a product that allows the user to keep hydrated during exercise through a mouthpiece (Halterman, TE; 2015). The product was primarily designed to keep the user’s hands free during exercise, but because of numerous applications of this product it has become less exclusive to running. The use of 3D printing for this concept is to prototype the function, which would have been difficult to do through another manufacturing method. As the use of rapid prototyping was confined to the testing stage with this project, the only attributes of rapid prototyping that could have benefitted this product are them that aided with the testing, such as the quick manufacture time, and not the final use of the product.

A similar product using similar processes is the GRITT
custom mouth guard, which is personalised for each individual user based on a dental scan (Halterman, TE; 2015). By basing the product on scanned data, this allows the product to have the optimised personalised fit, through modelling around the scan data. A comment from the interviewee for this article states that, the mouth guard “increases breathability, provides for improved ability to communicate and maximises comfort” (Halterman, TE; 2015). All of these aspects could collectively improve the athlete's individual ability, and possibly improve the overall team’s performance, but the theory behind this performance enhancement does need to be proved. The product can also be personalised for specific sports to have more or less material in certain areas, such as reinforcement around the front teeth for hockey players and extra protection at bite impact point for snowboarders. The author of his article referenced from the original interview that the developer of the product believes that it has performance benefits, but this is not backed up by any data.

The use of 3D printing for a custom-made product was also used for Japan's Olympic fencing team, which the team used when they reached the final of the 2012 Olympics. The author of the article stated that, “Part of the team's success” was rested on the 3D printed personalised hilts for each of the athletes (Newman, J; 2012). Each athlete was given five personalised hilts to ensure that they had one to use throughout the competition. As opposed to personally customised hilts, which can be impossible to replicate, these 3D-printed hilts can be made identical every time. This was the furthest that Japan has reached in any Olympic competition, both male and female events (Wikipedia, 2015)(Figure 4).

From intensive research into this particular area of interest, it was noticed that, the majority of useful information on this subject was recent literature as far as 2012. This could possibly be taken as a growth in the popularity of rapid prototyping within sport, or that it has reached a stage where it the capabilities are realistic enough to put in to full swing and not just on an experimental stage. This will be taken into account during further research into the subject area, so that information that is not as useful can be filtered out.

4. Research Methods
To be able to gain the most valuable and useful information for this project, the research methods need to be carefully considered. One of the research methods chosen is interviewing, these will ideally be aimed people involved with sports research related to 3D printing. Interviews with athletes that have experience using 3D printed sports equipment would prove very useful to his project, however the arrangement of this interview may prove difficult.

Further investigation and review of current and proposed rapid prototyping projects will also be another research method used through this project. These research methods will both provide qualitative information such as verbal data, which can be
interpreted (Explorable.com, 2009). The gathered information will not be as easily compared as the measurable data from quantitative research can be, but will more beneficial for this project. This is because the effectiveness of rapid prototyping will be evaluated more feasibly, by being based on opinions. For example, a user of 3D printed personalised tennis racquet may think that, the product aids their performance because it is more comfortable to hold, but it would be hard to prove through measurable data that it actually improves performance.

By reviewing and investigating further case studies this will identify how rapid prototyping is being implemented within sport, an also how it aims to improve performance. The use of case studies within sport research projects will provide a more realistic response over generally statistical processes, however it can be seen in most examples that case studies will give a very narrow spectrum of results (Shuttleworth, M. 2008). This research method will be beneficial to this project, as these specific examples will allow the application of 3D printing within sport to be critically evaluated. The use of this research method is valuable to the project as rapid prototyping in sports is currently utilised by larger companies, for which the only available information on the project is in the form of articles and documentaries. As identified in the literature review, the case studies are currently the main source of insights in to this area of research.

5. Research Tasks

The interviews undertaken through this project will be with rapid prototyping professionals, knowledgeable with the equipment design; and potentially sporting professionals, experience with using the equipment. These two specific targets will be able to provide the most viable and valuable information and opinions on the outlined research questions. The structure of the interviews has been carefully considered to address the research objectives outlined, so that the most important information can be extracted from the interview. The case studies will be based on live projects involving the use of rapid prototyping techniques for equipment used within sport. By studying the products being tested, this will identify how much potential the equipment has to aid with sporting performance. The case studies should also provide some personal insights in to the projects, such as the views of investigators on the projects and views from athletes experienced with rapid prototyping.

The proposed interviewees for those involved with the research and design stage will be the investigators involved with the Elite to High Street project coordinated at Loughborough University. This project has been chosen, as they are prime examples of the use of rapid prototyping techniques at a well-established additive manufacture department. Other proposed interviewees will also be part of a present of past project that is related to a different sport, so that a wider range of opinions, insights and results can be obtained. These projects will also be investigated through the linked case studies as well as the interviews, so that, the recorded results can be identified and evaluated. The further investigation into case studies will be focused at similar projects to this to gage a view of comparison between them, and also into looking at products that have similar cases of redevelopment, such as personalisation. By identifying more studies of projects that evolve around personalisation, then the performance effects can be reviewed more reliably.

6. Research Findings

6.1 Exploring The Uses of Various Types of Rapid Prototyping

As there are multiple methods of rapid prototyping, each with slightly different properties, but there is usually one more suitable to the application that the others. The process required is most commonly decided upon the type of material desired for the produced part. In the early development stages of additive manufacture, polymers were the dominant materials used as this is what the process was developed around manufacturing. As the technology has advanced the available materials for the use of additive manufacture has increased greatly, to now being able to manufacture parts from metals, ceramics, composites and even live cells for medical purposes (Ming, C and Nannan, G; 2013).

A research project was undertaken in 2013 which investigated the “Application of Additive Manufacturing Techniques in Sports Footwear”, which compared the
relative benefits of the various techniques for prototyping footwear. The four methods of manufacture in comparison are Stereo Lithography (SLA), PolyJet (PJ), Selective Laser Sintering (SLS) and Three-Dimensional Printing (3DP). The characteristics that the methods were compared on are: the accuracy of the part, the quality of surface finish of the part, the range of materials supported by the process and the building time by the process. The processes were compared by a five point scoring system and the results recorded (Table 1) (Manoharan, V, Meng Chou, S, Forrester, S, Boay Chai, G and Wah Kong, P; 2013). The overall summary in this paper emphasises how each of the manufacturing methods identified are all suitable processes for the challenge of prototyping trainers, but the selection must be based on the specific requirements for the individually prototyped trainer (Manoharan, V, Meng Chou, et al; 2013). For the instance of the Elite to High Street New Balance inner sole, Laser Sintering (LS) was used to produce the Nylon 12 inner soles to be experimented on (Gyi, D, Salles, A; 2012).

6.2 Elite to High Street Interviews

The Elite to high street project aimed to develop high performance sports footwear, optimised for the individual athlete. The uses of 3D scanning and rapid prototyping were frequent throughout the project. For this research project, 38 individuals were recruited; single blind trials with non-personalised soles and personalised 3D printed soles were used within this project. The participants were paired as equally as possible so that the only different between the pair was the type of inner sole (Gyi, D, Forrester, E and Salles, A; 2011). This was so that the results were unbiased, by the participants being unaware whether they were using the personalised sole or not. The interviews with investigators involved with the Elite to high street project gave many useful insights in to the effects gained from the project, and the project itself.

Dr. Gyi, who worked as a co-investigator on the project, focused on the ergonomics of the user's feet and looked into how the personalisation of the trainer sole could affect the user's ability. The interview with Dr. Gyi was useful in that the opinions of the effectiveness of the project provided were backed up by the facts obtained.

Dr Gyi stated in the interview that, “the comfort levels recorded were clear between soles” to distinguish that the personalised soles provided a more comfortable fit during usage. As explained in the relative literature, those using the personalised inner sole “demonstrated a less dorsiflexed ankle that may be related to a significant reduction in mean loading and lower impact force peak” (Gyi, D, Forrester, E and Salles, A; 2011). Dr. Gyi also stated during the interview that, project would have been “almost impossible to do without the use of 3D printing”, because of the intensive organic models produced. The inner soles produced during this project were designed from the scanned data acquired using 3D scanning equipment, to be like a “glove fit”. Laser sintering was the rapid prototyping technique used to manufacture the personalised inner soles for the participants (Gyi, D and Salles, A; 2012). The recordings and findings from this project could influence 3D printing further within sport, more so for personalised goods, Dr Gyi believes. The influence into more focussed projects such as special soles for people with foot/gait problems, to aid with improving comfort whilst walking, could also be influenced from this.

Dr. Porter, who was also a co-investigator on the Elite to High Street project, focussed their research in to the high street system with which the consumer will interact, and so the interview provided a different perspective on the Elite to High Street project.

Dr. Porter explained how they thought that, the proposal of the project aimed for high street retail was currently impractical, because of the manufacturing technology available. The reasoning for this was that, the possibility of

<table>
<thead>
<tr>
<th>AM Technique</th>
<th>Accuracy (5 points - most Accurate)</th>
<th>Surface Finish 5 Points - Best Finished</th>
<th>Supported (5 Points - Widest Range of Materials)</th>
<th>Range of Materials</th>
<th>Building time (5 Points - Shortest Time)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stereolithography (SLA)</td>
<td>3</td>
<td>5</td>
<td>3</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>PolyJet (PJ)</td>
<td>4</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>4</td>
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<tr>
<td>Selective Laser Sintering (SLS)</td>
<td>2</td>
<td>2</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Three-Dimensional Printing (3DP)</td>
<td>2</td>
<td>2</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 1. AM Techniques 5 Point Scoring System Results
personalised equipment at an elite level is currently scarce, and for it to be a commercially viable product sold on the high street the technology must evolve first. This provided an argument for whether the technology should be used more popularly within sport as it is currently lacking the development to functional on a large scale. Improved performance from the use of the personalised inner sole was acknowledged by Dr Porter, and advanced further to explain that, inner static jumping was the main measured benefit from the personalised inner sole. Showing that, the results of the project are enough conviction for her to vouch for the performance benefits enabled. Another possible effect of the personalised product outlined by Dr Porter was a greater attachment to it; by being manufactured personal to the user they may use it more frequently and for the duration. This effect linked on to the sustainability of the product, and what will happen to the inner sole once the product has been used.

6.3 Elite to High Street Journals

In company with the opinions gathered from the interviewees with the Elite to High Street project co-investigators, the Journals published throughout the project can also provide useful insights and information on the project, which is useful to this research. The journals outline how the investigation has been executed, the findings of the investigation and what this means in relation to the objective. Within the journals, the results are displayed through graphs, which provide some quantitative information on the equipment performance that can be analysed and evaluated.

The Elite to High Street project focused mainly on improving the comfort of footwear through personalisation, as comfort is the main aspect that is considered when purchasing footwear (Karwowski, W and Salvendy G; 2010). The outlined method of improving comfort is to produce a “glove fit” for each of the participants not using the control inner sole. Through doing this, it will allow the comfort of this fit to be compared to the standard fit, and what any other affects are. The control users wore New Balance NBO-757 trainers with a 3D printing sole that replicated the original inner sole throughout the experiment; and the personalised users wore the same trainers with the customised inner sole produced to the same thickness (2mm) and material as the control inner sole (Karwowski, W and Salvendy, G; 2010).

To test the comfort of the inner soles, the participants were expected to use the experimental trainers for their recreational running for the duration of the experimental stage. The discomfort was assessed using a Visual Analogue Scale to measure the self-perceived discomfort of six aspects of the foot (Karwowski, W and Salvendy, G; 2010). By rating the comfort provided from the sole at these six locations, this will indicate how the fit around the foot by the sole is affecting the user's comfort in each area. The participants were required to run at the same speed (2.78 ms-1 ±5%) for the trials during the experimental stage, this was for the project risk assessment, but also helped implement uniform conditions throughout the experiment. For each participant, five valid runs were measured where the pressure of three locations between the shoe and user’s foot were measured; and five valid runs where the user's motion was captured using 14 reflective markers. At this running speed (2.78 ms-1 ±5%), the comfort levels, running motion and pressure applied can be compared between the runners more easily. The analysis of the overall data showed that, there was a noticeable decrease in discomfort for the use of the personalised inner sole over the length of the project (Figure 5).

6.4 Individualising New Balance Running Spike Plates

A more recent additive manufacture project, also run by New Balance, investigated the personalisation of the outer sole of track running shoes to optimize it for the user's running style. Similarly, to the Elite to High Street project, the participants were subject to testing to identify the main pressure points created whilst running; and the personalised spike plate was designed around this data. It is stated within this article that, “No two runners are the same” (EOS; 2015), which explains why the user's specific running style needs to be identified in order to manufacture the outer sole to suit them personally. The outcome of this project was a personalised running shoe with custom spikes, manufactured from a custom nylon...
The results of this project show that, the manufacture method provided a 5% weight reduction in comparison to traditionally manufactured versions. Kim Conley, a member of Team New Balance and a U.S.Olympic runner, was a participant for this project where they had numerous running shoes manufactured around her running data. Kim explained in an interview with New Balance that, she believes the trainer makes a difference to her performance; this may be because she has run personal records in the 3000 m and 5000 m wearing the personalised shoes. She also wore the trainers during the 2013 World championships, where she had her best performance to date. Conley also stated in the interview that her shoes are critical to her performance and that they are “the most important piece of equipment I have” (EOS; 2015).

6.5 Open Source 3D Printing

The widespread use of 3D printing across the world has enabled a lot open source material for the public to obtain. This open source community can aid with the development of hardware and software by allowing public access to the data, and it can also be used to provide the public community with free software available for download (Horvath; 2014). In most circumstances the work can be privatized through careful patents, which will stop the work from being replicated as another piece. This is usually avoided through certain licenses that ensure any modifications to software; for example, any modifications to the software are made public to the community that it was originally shared on (Horvath; 2014). A case where the use of an open source community could have been damaging was the possibility of releasing 3D printed gun blueprints publicly. Defence Distributed, a weapon hardware company, had planned to make the blueprints available online, but because of the huge criticism the release was halted. The criticism was mainly due to that the publication of a firearm, the impacts this would have on general safety and what this would mean to gun licensing if weapons could be obtained so easily (Morelle, R; 2013). This is applicable to a sporting scene because of the possibility to share data that can be personalised, which could in turn benefit others athletes that require similar equipment.

7. Discussion

The investigation into what variations of rapid prototyping are used within sport brought forward a few ideas of what process should be used for which application. Selective Laser Sintering was identified as the process that would work best with a flexible material, such as rubber, because of the extensive range of materials applicable through this process. The use of flexible materials for application within sport is important for the personalisation of equipment, especially wearable items such as trainers, because of the movement that is allowed in the product to adapt around body movements. Each of the processes investigated in the “Application of Additive Manufacturing Technologies in Sports Footwear” could be applied to a sports scenario other than in a running environment; the processes that can be applicable with metals would be...
applicable to many more environments, such as cycling and motor sports.

From the four main rapid prototyping materials outlined: polymers, metals, composites and ceramics; each could have an influence within a sporting application. Examples of the use of metal have been explored with Sir Bradley Wiggins custom titanium handlebar; the Hydraguard made use of manufacturing with polymers; and the use of ceramics and composites could very easily have been used for a similar application within sport. The general low weight of ceramic materials, such as carbon fibre, provides a lot of opportunity for the use of this material within sport in such sports that require the most lightweight equipment available. The use of composite materials could utilize their unique properties within a sporting application.

The manufacturing process, Laser Sintering, used for the Elite to High Street project experimental inner soles could possibly have been selected due to the capability of printing in a range of materials (Manoharan, V, Meng Chou, S, Forrester, S, Boay Chai, G, Wah Kong, P; 2013). The material used for the trainer inner sole, Nylon 12, is not a very common material in rapid prototyping because of the difficult flexibility; and so an advanced rapid prototyping technique is required to use it (Gyi, D, Salles, A; 2012). The capabilities of Laser Sintering that enabled the Elite to High Street project team to produce the inner sole geometry, which would have been otherwise impossible to do on the same time scale, is one of the main benefits of rapid prototyping process. This is also one of main ways that rapid prototyping will change sporting equipment, as it allows complex organic products to be produced easy and quickly. The personalised handlebars that Sir Bradley Wiggins used to beat the lap record were also manufactured through this rapid prototyping technique (O’Connor, D; 2015). This is another example of how a very personalised product with complicated geometry was produced within a small time frame by a rapid prototyping technique, strongly supporting this as one of the main benefits of the technology. The ability of the process that allowed both of these exampled projects to be accomplished was aided very much by the quick manufacture times possible through this process. The production of a one off handlebar based around custom geometry would have taken any other manufacturing process a much longer time to produce the same artefact, if even possible at all.

The primary research completed for this project, in the form of interviews, proved very useful to the project by providing valuable opinions on and insights in to the use of 3D printing within sport. The interviews with co-investigators from the Elite to High Street project showed a few views on and impacts from the use of RP within sport. The performance benefits of the customized inner sole were acknowledged by both of the interviewees; and in this case the benefit was caused primarily through the personalisation of the inner sole. This personalisation of the inner sole mainly meant that there would be an increase in comfort whilst wearing and using the product; and from this improvement in comfort the change in user’s foot biomechanics improved the performance of the user in aspects such as static jumping. This performance benefit was through a reduction in pressure on areas of the foot and a reduction of dorsiflexion in the user’s foot on strike impact. This fact that the rapid prototyped inner sole was capable of improving performance through personalisation could mean that if more of the standard training shoe was improved through rapid prototyping techniques, then the performance enhancer could have been greater. The increase in comfort may also be transferrable to other sports such as tennis, but in a way that could improve contact with the ground during sharp movements.

An insight raised in the interview with Dr Gyi was that the popularity of personalised 3d printed goods could be increased through the influence of the Elite to High Street project. This could create an influence throughout the sports industry to bring products to athletes who wish to have a personalised training item, to aid their performances physically and psychologically. If the popularity of the use of 3D printing with sport were to increase, due to a knock on effect from this project then the technology would evolve towards the mainstream trends, which could make the use of 3D printing more
practical over the long-term. As there is a desirable characteristic about using a personalised item, this could be the link required to bring the technology in to other sporting areas, but not necessarily for the performance aspects.

Identifying that a personalised fit could improve performance through this project may trigger an interest in to what could be achieved further from the personalised inner sole (Gyi, D and Salles, A; 2012). This could mean that sporting equipment, for elite athletes, is caused evolve to be more focused around personalisation, to be able to achieve the highest-level performance as possible. This could alter the manufacture of sports equipment, to sway towards the use of rapid prototyping rather than advance to achieve the potential capabilities of 3D printing. The customisation of other products to gain a personalised fit could be applied to other sports where a piece of equipment is used closely around human body, such as a personalised javelin grip. The application to other sports could give the potential to improve the geometry of the piece of equipment and the benefits that are enabled.

The journals published by the Elite to High Street project shows how the desired "glove fit" from the personalised inner sole was achieved through the use of rapid prototyping (Gyi, D and Salles, A; 2012). To be able to sculpt a product around personal geometry, the process used needs to be fully adaptable to other body shapes in order to replicate various personal geometries. This shows how versatile the process of rapid prototyping is in general, as an undefined amount of variation between products can be manufactured using this one technology.

It was also evident from the journals that the results of an increase in comfort from the personalised inner sole, was backed up by data gathered from the participants (see figure 6). The results in the tables show that over short-term use, the discomfort caused from the use of the personalised inner sole decreased for each of the individual areas of the users' feet. It is portrayed through the discomfort of the overall fit that the discomfort has decreased over short-term use. This is one of the main parts of the project that show success in what was set out to be achieved, to evaluate the effects of personalised inner soles on the user (Gyi, D and Salles, A; 2012). The evidence from this project provides a good argument for the application of rapid prototyping for sporting performance benefits, as it can be seen through the results that an improvement has been made.

From the investigation in to similar rapid prototyping projects, it was seen through the use of personalised 3D printed running spikes by Kim Conley that the use of the product had the potential to guide her to personal records in two of her events. Kim stated in an interview with EOS that she believed that the personalised spike shoes aided with her performance, and also emphasized how they were a very important piece of equipment (EOS; 2015). This could provide an argument towards the personalisation of footwear improving performance, not only because of the results achieved by Conley, but because of the backing up of the point through similar projects such as the Elite to High Street. The effects on performance caused by rapid prototyping can be evaluated across this specific area of sport, running trainers, but this does not provide enough evidence to evaluate it across the use within sport. There is, however, a slight backing of the benefits of using rapid prototyping to create personalised geometry, as this has been seen achieved through multiple sporting scenarios.

A separate accomplishment of the New Balance personalised running spike project, other than those of Kim Conley, was the achieved reduction in weight for the running spikes produced. The use of rapid prototyping allowed the geometry to be edited in a way that removed 5% of the material in the shoe, and so a 5% weight reduction was achieved. This benefit of the process is one that could be transferrable to multiple other sporting scenarios, as in high level sports competitions weight can be a major factor on the selection of equipment.

The development of sporting equipment within an open source community could allow a widespread of the available technology for both elite and amateur athletes to utilise. This means that the possibility of manufacturing personalised products could be made much more
available, to those with access to rapid prototyping equipment. Alternatively to this, the software could be privatised so that it is only available to those that can afford to pay for the data; which could mean that the customisation of goods would stay exclusively on an elite level. This is one way that rapid prototyping could widespread through sport, and how it could affect sport in the future.

Conclusions

Through the examples explored within this piece a variety of forms of rapid prototyping have been used, such as Selective Laser Sintering and High Speed Sintering. This shows how each variation of the process is widely used and each task selects the most preferable process to benefit the project. The appropriate processes chosen for the application within sport does correlate to side towards Selective Laser Sintering due to the popularity and the materials available for use with this process. This is because the majority of personalised products require some degree of flexibility to be manipulated around the human body, which can be achieved through the use of flexible materials bonded through the Laser Sintering process.

From the examples reviewed the main difference between sporting equipment produced through a 3D printing technique and those not, is the aspect of the individualisation of the product. This aspect of each product, being produced as a stand-alone product rather than a uniform cloned one, gives a unique personalisation to the artefact. This alone could provide the main selling point of a commercialised product, over the other benefits that the process can provide.

From what has been investigated about in this research project, it could be suggested that other manufacturing technologies haven’t been developed to compete with rapid prototyping, only more industries embracing it. This could be because the desirability of the rapid prototyping benefits cannot be embraced by other technologies that could be improved by doing so. The unique form of personalisation would be almost impossible to recreate with an alternate method of manufacture, such as injection moulding, as it would be very time consuming and expensive to manufacture individual mould tools for each of the personalised products. Sporting equipment could be changed through rapid prototyping in a way that the highest standard of equipment cannot be produced in any other way. As shown through the example of sir Bradley Wiggins 3D printed handlebars, which allowed the creation of the most aerodynamic handlebars made possible (O’Connor, D; 2015). This showed that, more can be achieved through improving equipment geometry, through the use of rapid prototyping, and also what could be possible improved in other scenarios that involve the highest of standards of parts.

One of the main benefits of rapid prototyping, as repetitively identified, is the ability to produce abnormal geometry that could be difficult to do so by the means of another manufacturing process. Advancing from this benefit brings the ability to produce lightweight products by utilizing the complex geometry achievable. Another benefit is the availability of production, that any CAD model can be manufactured using rapid prototyping in a relatively short period of time. The ability of producing complex geometry through this process, which allows personalisation of sporting equipment, could cause manufacturing processes to sway towards rapid prototyping. All types of manufacture for sporting equipment, especially on an elite level, could be alternated to rapid prototyping because of this ability to create personalised products.

The Elite to High Street project and the New Balance 3D printed running spikes showed through results that the personalisation of sporting equipment has the potential to benefit performance within sport. These findings have been more focussed around the personalisation of the product, rather than the manufacturing process as a whole, as this is the main factor that could affect the user during sport. This was also discussed regarding the achievements of athlete Kim Conley, who used rapid prototyped running spikes whilst gaining personal records in two races. Conley also stated in her interview with EOS, that she believes the personalised footwear have an impact on her performance and expressed how much of
an important factor the trainers are to her achievements. These examples however, are both explicit to a running scenario where the only equipment is running shoes; and so this does not prove the performance benefits across all disciplines of sport. To be able to explicitly state that the manufacturing process is responsible for an improvement in sports performance, research in to a larger variety of sports is required.

An interview with an athlete would have been very beneficial to the research of this project, by possibly providing primary information that gave views on this subject from an alternate point of view. This would have also provided insights in to how the rapid prototyped product differed from a standard similar product in terms of how it feels, and what impact it had on the user’s performance; not just physically but also psychologically. Some of the main arguments for performance benefits being provided through using rapid prototyping techniques could have been gained from useful experiences shared by an athlete, explaining what about the equipment aided them.

From all of the benefits identified through this research, the one more strongly desired for the most applications is the ability to create complex geometry. This can be examples as the most desirable aspect of rapid prototyping within a sporting scenario, as of the range of applications this can be useful for. This was shown through the examples of sir Bradley Wiggins’ personalised handlebars and Kim Conley’s personalised shoes, which both exhibited complex geometry in order to create the personalisation.

Overall from this investigation it can be confirmed that rapid prototyping technologies have the potential to provide performance benefits, whether it be through personalisation, improved geometry or speed of one off manufacture. It cannot be confirmed, however, that the use of rapid prototyping technologies will improve performance within sporting instances in general. This is because the technique has not been proven to provide these benefits in all instances that it has been applied to.

References


ABOUT THE AUTHOR

Tom Page is a Senior Lecturer at Loughborough Design School, United Kingdom. Tom’s background is in avionics and he worked as a Development Engineer for Ferranti Defence Systems Ltd. in Edinburgh. In 1990, he took up a two-year fixed-term research assistantship at the Engineering Design Research Centre in Glasgow. Upon completion of this role, he taught Computer-Aided Engineering at the University of Hertfordshire in Hatfield. Since moving to Loughborough University in 2003, Tom has taught Electronic Product Design, Interaction Design, Design and Manufacturing Technology and Physical Computing. His research interests are in Engineering Design, Design Education, Technology Education and Electronic Design Automation. He is the organiser and co-ordinator of all design and prototyping activities required for the Engineering Education Scheme (EES) workshop and is the outreach and widening participation coordinator within the Design School. Tom’s work has been widely published in the form of Journal papers, Book contributions, refereed Proceedings, refereed Conference papers and Technical papers. He has supervised research students, acted as external examiner on undergraduate and postgraduate programmes, examined PhDs and MPhils and has acted on the reviewing panel of a number of key Journals and Conferences.