3D-printing: A Future “Magic Wand” for Global Manufacturing
How Can We Benefit from It Today for Sports and Health Care?

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Abstract: 3D-printing, or as it is also known, additive manufacturing (AM), is promising to be one of the determining manufacturing technologies of the present century. It is not a single technology but a family of rather different ones common in the way components are made, adding materials layer by layer. Additive manufacturing is already quite competitive to existing and well established technologies, but it also can provide unprecedented flexibility and complexity of shapes making components from the materials as different as cheese, chocolate and cream, live cells, concrete, polymers and metal. Many more materials we were not even thinking about few years ago are also becoming available in additive manufacturing, making it really believable that “only the sky is the limit”. During the time available for the keynote lecture, we will analyze the present position of AM in relation to other technologies, the features that make it so promising and its influence upon the part of our life we call sports and health, using the examples relevant to the Congress areas from computer systems to sports performance. Out of all enormities of materials available for different representatives of this manufacturing family we will concentrate at polymers and metals. AM technologies working with these two material families are already providing some unique solutions within the application areas relevant to the Congress' scope. We will also talk about some limitations inherent to the AM in polymers and metals to have the awareness that though the limit is somewhere “high in the sky”, it still exists.

1 INTRODUCTION

Additive Manufacturing (AM) is a proper term describing technologies that build objects by adding layer-upon-layer of material (Christensen et al, 2007). 3D printing, the name commonly used in everyday life, is in fact only one of the technology types in this family, and many other AM technologies can hardly be referred to as “printing”. Materials used in modern additive manufacturing can range from concrete, rubbers to polymers, metals, cheese, cream and chocolate. In the big family of additive manufacturing different technologies have different levels of “maturity”. AM in polymers and metals (alloys) represent most mature methods that already compete with many other, well established technologies especially in manufacturing small series or unique products. Competitive advantages of these methods include the ability of building components with extremely complex shapes in a single technological process, fast design-to-market times, high energy and material efficiency (Koptyug et al, 2017, Nanotechnology). Along with materials common with other technologies additive manufacturing in metallic materials and polymers introduce new materials not available for other technologies (e.g. Koptyug et al, 2013 AM Conf., Pauly et al, 2013), utilizing unique inherent properties of used processes. Wide applications of modern computer and virtual reality technology integrated into “the design for AM” process allow for unique versatility in functionalization, individualization and modification of the manufactured components almost without increasing production costs. Current paper presents some of the experiences in integrating additive manufacturing into the education, research and development within healthcare, sports and active lifestyle technology- related applications from Sports Tech Research Centre at Mid Sweden University.

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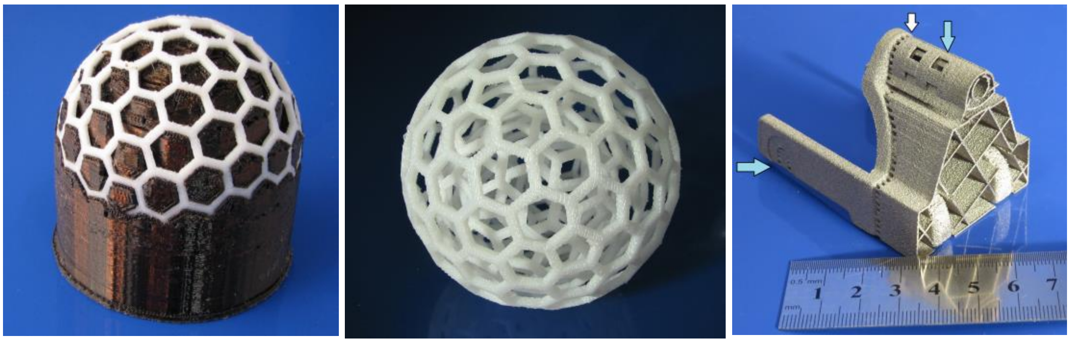
2 MATERIALS AND METHODS

A set of additive manufacturing machines is stationed at Sports Tech Research Centre, including one high-end device working with metals and alloys, two high-end industrial class polymer machines, and five table-top polymer ones. Table-top polymer machines are mainly used in education within the BSc and MSc engineering courses related to modern design and manufacturing, and graduate exam projects (Bäckström et al, 2013). High end machines are used both for research and development, and as the means of manufacturing of unique parts and components. Majority of the described examples relate to the components and parts manufactured using these machines.

For additive manufacturing in metals and alloys we use an ARCAM A2 Electron Beam Melting machine by ARCAM AB (Mölndal, Sweden). Electron Beam Melting is a powder bed fusion additive manufacturing method, where successive layers of metal powder are melted together with a high power scanning electron beam (Sames et al, 2016, Koptyug et al, 2017, MSF). The process takes place in a vacuum chamber at high temperatures. Powder is brought to the working zone forming a thin layer (commonly 50 to 90 micron- thick). High intensity electron beam melts the area corresponding to solid sections at present component height. Working table is lowered one step (thickness of one production layer), powder is brushed over the working area again, and the process of next layer processing is carried out. More details about the process stages can be found elsewhere (Sames et al, 2016, Koptyug et al, 2017, MSF). Currently we mainly work with the titanium alloy Ti6Al4V (Koptyug et al, 2017, Cronskär et al, 2012, Koptyug et al, 2013, LSMR), an alloy well known to medical, aerospace and automotive industry and common to many powder-bed AM methods, and at introducing new materials earlier not used in AM (Koptyug et al, 2013, AM Conf., Zhong et al, 2017).

High-end additive manufacturing in polymers is represented by fused deposition modelling (FDM) machine Stratasys uPrint and PolyJet machine EDEN260V, both by Stratasys Ltd (Stratasys Ltd, 2017). FDM machine uses a thin filament made of a thermoplastic polymer, which is melted and extruded in thin adjacent “wires” forming manufactured component layer by layer. It can make components up to 203 x 203 x 152 mm in size with the resolution about 0.1 mm. PolyJet machine operates in a way similar to an old bubble-let printer, only instead of liquid ink it uses monomers depositing them layer and curing it by a UV-lamp. It can make components up to 255 x 252 x 200 mm, and its precision is given in dpi, as for the true printer: 600 dpi in the layer plan and 1200 dpi in the build direction. It means that in the high resolution mode its precision is about 16 micron. And when the FDM machines are rather limited to the type of materials (relatively stiff thermoplastic polymers) PolyJet ones have much wider choice, from softer rubber-like to relatively hard polymers, transparent or having different colours. Table-top polymer machines MakerBot Replicator (Makerbot LLC, 2017) are also of the FDM type. Though sizes of components it can manufacture and precision are not as impressive as for the high-end machines, these are easy to use and interface. These machines are mainly used for prototyping, and mainly for education. It should be noted here, that with manufacturing of



(a) (b) (c)

Figure 1: Complex shape components manufactured from ABS polymer in the FDM machine (a, b), and from Ti6Al4V in the EBM machine (c). Polymer component is shown as it comes out from the machine, when support material covers essentially all voids (a), and after support removal in the ultrasonic bath (b). Ti6Al4V component (c) is shown after removal of the surrounding working powder. Arrows mark the position of the wafer supports, and perforated support boundary where it will be broken off during post-processing.

complex shapes with overhanging features it is not possible to avoid using supporting elements in the manufactured component. In case of polymer machines a second, "support" polymer is used, commonly removable by water or special water solutions. In the case of metal machines supports take shape of wafer-thin elements, which are mechanically removed in post-processing. Figure 1a presents an examples of a "ball-in-ball" manufactured from ABS polymer in the FDM machine (a, b), and a component manufactured from Ti6Al4V in ARCAM A2 machine (c). With the polymer part (Fig. 1 a, b) working material is white and support material is dark. With the metallic parts supports are made in the same material. In Fig 1(c) blue arrows show the positions of the support wafers, and white arrow marks the perforated boundary of the supports, along which they will be broken off in post-processing. It is also clear, that one of the restrictions in "design for AM" for these types of machines. If we leave closed voids inside the components, they will be filled with a support polymer, or working powder, as it is possible to remove support materials in post-processing only through openings and channels.

3 AM IN HEALTHCARE

There are some application areas that already strongly benefit from actively using additive manufacturing. Industry is commonly the first to be mentioned, but areas related medicine, health care, and rehabilitation are also among clear beneficiaries (Koptyug et al, 2013, 2017). High competitiveness of the sport activities and certain risks inherent to active lifestyle can unfortunately result in injuries. Injury prevention is of course one of the best strategies to go for and some contributions of additive manufacturing to preventive strategies will be discussed later in this paper. In present chapter it will be discussed what AM can do for the medical treatment and rehabilitation.

3.1 Biomedical Implants

Orthopaedics and reconstructive surgery is already recognizing the advantages of additive manufacturing. While some other medical disciplines start discussing future possibilities of the medical treatment individualization, orthopaedics and reconstructive surgery already practice it with the help of additive manufacturing. Today it is possible to go all the way from medical image to individualized implants placed into the human body using design and manufacturing methods developed for or within AM technologies (Cronskär et al, 2008, 2012, 2013, Koptyug et al, 2013, LSMR). Today the advanced path from the results of medical scan to individualized implant looks as follows. During the first stage a standard image set acquired form medical 3D imager is transformed to the format that can be used by engineering and design software. Next, special software is used to "filter out" unnecessary features. In the case of designing individualized metallic implant or fixation plate for the broken bone one needs to "filter out" all soft tissues and cartilage from the original image, leaving only the bone outlines. Though it is not a trivial operation, number of commercial software packages capable of doing it is already available. Result of these operations is an exact computer 3D model of the bone, with all defects and brakes. From this point the path splits. "In real world", a replica of the broken bone is additively manufactured using a computer bone model (Fig. 2 a). "In virtual world", broken bone is mended using mirrored image of the symmetrical healthy bone as a template, with all bone fragments that are to be saved in the exact places. Next, perfectly fit individualized implant with screw hole positions and all other demanded details is designed (Koptyug et al, 2013, LSMR, Cronskär et al, 2008, 2012, 2013). It should be noted, that today "virtual world" line does not end with the shape optimization of the implants. Using advanced body modelling software packages one can calculate the values and directions of the forces applied to the bone by attached ligaments in a chosen scenario (Fig. 2 b, from Cronskär, 2014). And it is possible to model and calculate corresponding stress fields in both the broken bone and implant attached to it. And implant design now can be adjusted and optimized for the chosen functionality (lowest weight with given loading capacity, minimum thickness with excessive strength etc., Cronskär, 2014, Cronskär et al, 2013). Effectively, this is a process combining advanced shape and function-optimized design and "virtual surgery" of the broken bone mending. Now the implant itself is ready to enter the real world, and it is manufactured in one of the metal AM machines. At this point a preoperative model of broken bone "meets" matching metallic implant, both components additively manufactured in polymer and metal respectively (Fig. 2c). To speed up a pre-operative process in complex cases additional model of the implant can also manufactured in polymer, allowing surgeons to practice even before the

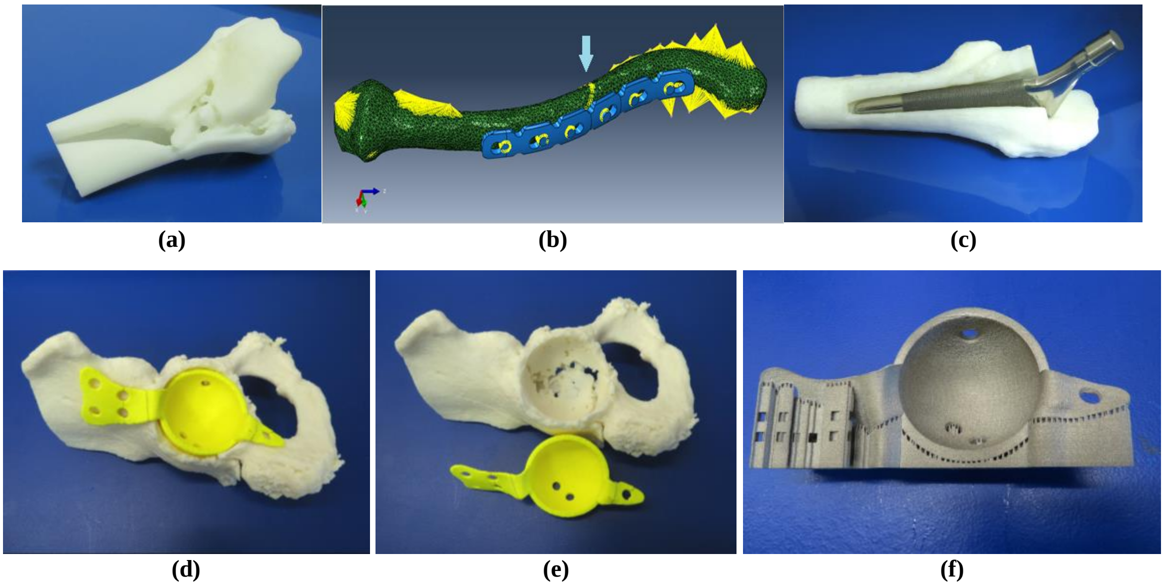


Figure 2: (a) Actual size pre-operative model of the broken bone manufactured from the ABS polymer basing on the medical image of the patient’s bone. (b) Computer model of the broken collarbone (clavicle) with a fixation plate attached. Arrow marks the brake position; yellow lines indicate directions and values of forces applied to the bone by attached ligaments. (c) Actual size ABS model of the thigh bone (femur) section showing the position of the individualized Ti6Al4V implant designed for the hip replacement surgery. (d, e) Actual size models of the human pelvis section and of a customized implant used in pre-operative planning; (f) corresponding implant made in EBM machine from Ti6Al4V with support structures still present. All given examples are from the medical case studies.

metallic implant is made. Figure 2 (e-f) illustrates a case for the hip replacement operation planning with the help of additive manufacturing in the case when pelvic bones are osteoporotic and acetabular cups with standard fixation cannot be applied. In such case individualized acetabular cup integrating fixation elements with the screw holes corresponding to parts of the pelvis where the bone is still strong enough is designed and manufactured. Figure 3(f) shows such cup as it comes after working powder is removed, but with the support structures still attached (positioned as it would be oriented in manufacturing).

Described path allowing “transitions” between virtual world of computer models and real one can be extended even further, for example towards manufacturing individualized surgical support tools. Using computer models of the bones one can manufacture saw guides for fast and precise removal of the damaged bone sections, and screw guides, allowing putting screws in exact places with precise orientation. As a result, modern surgeon can obtain a package of parts including a pre-operative bone models, optimized in shape and functionality implants and surgery support tools. And even before the patient goes to the operation theatre surgeons can perform a full-scale “dummy surgery” using actual size plastic bone models, individualized saw guides and implants- cutting, drilling and putting screws in place. Such preparation and availability of the individualized implants can significantly shorten the operation time and cost, and improve the procedure outcomes for the patients (Koptyug et al, 2013, Cronskär et al, 2008, 2012, 2013). Realizing market opportunities polymer AM machine manufacturers are now introducing the materials that can be sterilized and taken directly into the operation theatre.

Discussions about the benefits of additive manufacturing for biomedicine always involve delivery time and cost related issues. It appears that today design of the individualized implants takes most of the image-to-product time, and it should be done in tight cooperation between AM-able designers and practicing doctors. Polymer pre-operational models and metallic implants also need certain time to be manufactured, quality controlled and properly prepared for transferring to the hospital environment. Our experience shows that with the availability of proper resources, image-to-model times can be as short as 48-72 hours, and image-to-implant path can take less than 5-7 days (depending upon the complexity of the implants needed). Our best achievement was a lead time of 48 hours from receiving a medical image to the delivery of the finished implant. With the complex surgical procedures, where application of the individualized implants is effective, surgery preparation also takes time of at least about one-two weeks. Speaking of the costs, one needs to think of them even in the cases when individualized implants make a difference for patient between permanent disability and relatively normal life for a number of years. Comparisons of the costs associated with the additive manufacturing of individualized implants indicate that they are at least 30-40% cheaper than individualized implants manufactured using other technologies (Cronskär et al, 2013), and with increasing numbers of manufacturing sites capable of AM this ratio continues to improve. As compared to the "standardized" implants used in complex surgical cases additively manufactured implants are as such more costly. But when the reduction of surgery time is counted for, overall hospital costs are either on par or, in many cases, is significantly lower when using AM implants. Of course it would be hard for AM implants to compete in cost with relatively simple, mass-produced items. Thus at present highest value AM implants usage will bring in special surgical cases (complex fractures, osteoporotic bone cases, complex reconstructive procedures etc.).

Implant manufacturing is among the most challenging for additive manufacturing. Along with the issues common with almost all other technology and engineering applications of AM like: providing good value for money and acceptable costs, adequate design-to-market times, exact replication of the designed shape at the output, securing mechanical strength, fatigue and corrosion resistance, biomedical applications impose additional ones (Koptyug et al, 2012, 2014, 2017, Nanotechnology). Majority of these additional demands are related to biocompatibility of the implant material, its biointegration and longevity in the human body. For example, corrosion resistance in technology mainly presumes that component should not lose its mechanical properties. But even relatively small amount of ions "leaking" from the metallic implant into the body may be harmful. Also, because molten metal in powder- bed AM methods is surrounded by the working powder, component outer surfaces are always coming "as manufactured" rough to some extent and can contain loosely attached powder grains. Some technological applications demand much better surface finish and thus certain post-processing is performed. In ideal case surface topography control of biomedical implants should cover the feature dimensions from nanometres (determining wet ability and water contact angle important for the earliest stages of implant integration with cell attachment to the surface) through micrometers (important at later stages with cell migration and differentiation) to millimetres (providing vascularisation and bone ingrowths for better implant stability; Koptyug et al, 2012, 2014, 2017, Nanotechnology). Such control is not possible within existing additive manufacturing processes, and even needed post-processing often becomes hardly possible. Loosely connected surface powder grains may potentially become loose during service life, and thus should be secured or removed. For solving these issues research and development work is carried out across the world. Such work is aiming for example at improving AM processes in cases when components have solid and lattice sections, which can be additively manufactured in a single additive process. Such structures are important both for the implants (mimicking cortical bone structures) and for industrial applications (3D lattices in filters and catalyst carriers, in lightweight construction elements- integrated with solid component sections). Also significant efforts are directed to introducing better biocompatible materials for AM (Koptyug et al, 2014, 2017, Nanotechnology), and better methods for metallic implant surface coating (Surmenev et al, 2014, Surmeneva et al 2015, Chudinova et al, 2016).

Yet more problems are coming from the fact that solid implants used to fix and support broken or weak bones are much stronger than bone tissue. This often results in the situation when additional stress appears in the bone sections adjacent to the implant? For example, when solid titanium rod of the hip stem implant is sitting inside the osteoporotic thigh bone (femur) after hip replacement surgery, upper part of the bone up to the joint is than well protected from extra loads. But the area, where the "rod" ends will be under considerable stress, if the patients occasionally falls in a wrong way, and secondary brake in this position is quite probable. Differences in the mechanical properties of the metallic implants and bones can also lead to the loosening of the implant in the body after some time, either due to damaging surrounding bone, or to so-called "stress shielding", when bone tissue adjacent to the implant starts to "dissolve" (Huiskes et al, 1992, Summer, 2015, Koptyug et al, 2014). Today two possible ways of solving this problem are dominating research activities: development of new metallic materials with the mechanical properties closer to the ones of natural bone (e.g. Niinomi et al, 2011), and application of the implant sections that are porous or made of three-dimensional lightweight constructions (lattices; Heinl et al, 2008, Murr et al, 2010, Koptyug et al, 2012, 2014). But one should admit that no optimal solution is yet available for the everyday medical practice.

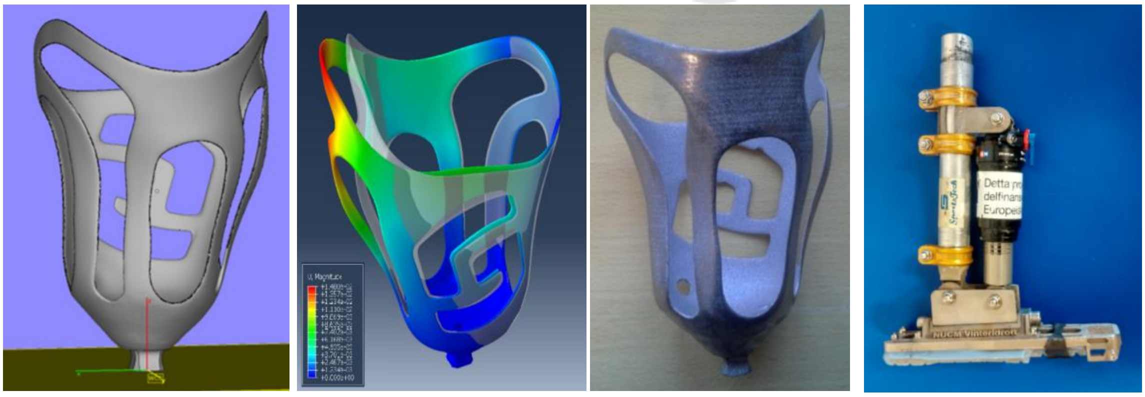
Though limitations of additive manufacturing in supporting treatment of broken bones exist, related progress in practical surgery related to AM implementation is quite significant allowing one to speak about introducing “spare parts for human body” (Bäckström et al, 2012, Zadpoor et al, 2017). Though such spare parts are not yet ideal and cannot completely substitute natural bones, they still help to return to activities and save lives.

3.1 Rehabilitation and Protection

Additively manufactured components significantly broaden the possibilities in supporting active patient rehabilitation after illness or injury. Individually fit protection, fixation and support devices can be manufactured for example with the help of additive manufacturing (e.g. Bibb et al, 2014, Palousek et al, 2014, Mills, 2015, Ganesan et al, 2016). Availability of the inexpensive, often hand-held digital scanners, availability of affordable and the emergence of free digital design software, and wide availability of both professional and table-top “3D printers” working with polymers boost public access to the individualized rehabilitation and protection devices. Because the extreme precision of digital scanning and manufacturing in many protection devices is often not needed, it allows keeping their cost relatively low

It should be noted, that as with many other additively manufactured components, production of such devices is not the most expensive stage, and dominating costs commonly lay with the design process. This difference is quite pronounced with the applications of additive manufacturing in prosthetics (e.g. Jina et al, 2015, Skoglund, 2015). In many cases individualized prosthetic device is the only option for having active lifestyle and participation in sports. As compared to many temporary protection devices prostheses should be designed for individual fit baring in mind their functionality, comfort, possible excessive loads and fatigue during service. And because in additive manufacturing cost is mainly associated with amount of used material and processing time rather than component complexity (“complexity comes for free”, Fera, 2016), prosthetic devices now can afford elements of the artistic design. Figure 3 (a-c) illustrates the process of an individualized prosthetic socket design and manufacturing (Skoglund, 2015). Digital model is designed basing on the individual scan (Fig 3 a) and is “virtually tested” in realistic loading conditions (Fig. 3b presents the deformation field in the Ti6Al4V socket during loading with clamped fixation element- small pyramid in the bottom of the socket). Sports Tech Research Centre logotype (stylized letter S) is incorporated into the socket to illustrate possibilities of artistic touch to the individualized prosthetic devices.

Today functional prosthetic devices and individualized equipment are becoming available and are actively used by many Para-athletes (e.g. Pallis, 2003, Technology for Disability Sport, 2016). For many of them only such devices allow them to compete. Figure 3(d) presents the low leg prosthetic device successfully used in training and competitions by Swedish Nordic skier Helene Ripa (Helene Ripa, 2017). It has relatively simple



(a) **(b)** **(c)** **(d)**

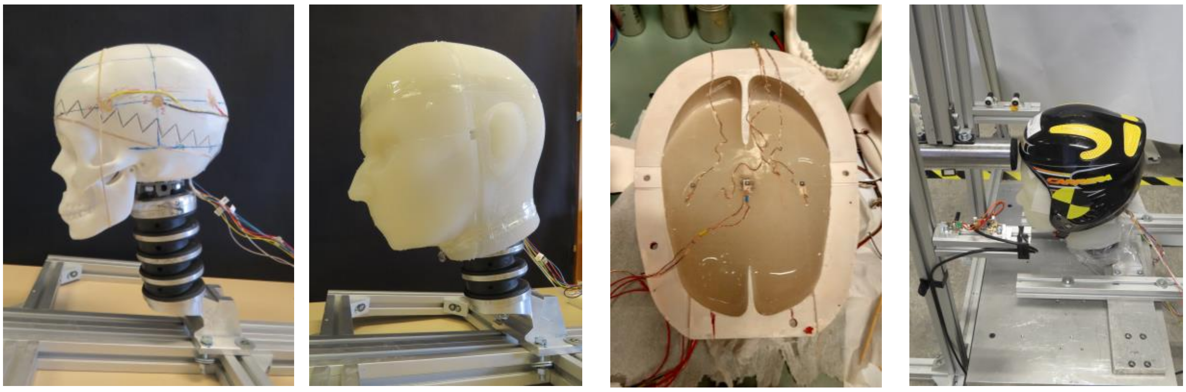
Figure 3: 3D design model for the manufacturing of the individualized prosthetic socket for a knee amputee (a), computed deformation field during its loading (b) and final component manufactured using EBM technology in Ti6Al4V (c); lower leg functional prosthesis for the Nordic skier (e).

mechanical construction and incorporates bicycle air type adjustable shock absorber with some parts in this first prototype made in Ti6Al4V using EBM additive manufacturing. According to Helen, this device allows for the leg movements much closer to what she has had before the injury. So the engineers have done a good technical job, but at the time were lacking the knowledge on the rules and regulations for competitions by the International Paralympics Committee (IPC). According to these rules (see IPC rules for Nordic Skiing) devices like the one shown in Fig. 3(d) that are directly connected to the ski bindings are not allowed in the IPC competitions, the ski shoe must be always present. So the device was re-designed and manufactured using simpler and off-shelf components.

4 INJURY PREVENTION

Additive manufacturing is not only actively helping with medical treatment and rehabilitation, but becomes an important tool in injury-prevention research. It is quite important to understand how injuries happen in order to prevent them. We realize that the most important part of the scientific method is the experiment. But experiments leading to injuries are belonging to a nightmare scenario. Thus in many cases the only experimental evidence available for scientists would be the unfortunate results of an injury or trauma. Modern science has certain tools that can be used for reconstructing the events. Mainly this is done using computer-based modelling. In modern days such modelling often involves what we call “virtual reality”, allowing to “perform experiments” that could be dangerous in real world (or expensive, or lengthy in time, or under conditions which never exist in real world). Typical examples of this approach are related to designing safety devices protecting human body parts from injuries resulting from the falls or collisions. Modern medical equipment is capable of producing detailed scans (high spatial resolution and specificity to the type of the tissues) of the body parts. Basing on such scans computer models of corresponding bones, or of the whole body parts, are made. In case of damaged body parts it is possible to make virtual reconstruction of their “intact” state, and model the conditions that will cause damage we registered experimentally. One can also generate models of the body parts together with safety devices and perform multiple “virtual experiments” assessing the efficiency of the protection.

Among various devices protecting us in sports and other activities with the help of mathematical modelling and additive manufacturing one can find the ones designed to protect our legs (e.g. Emerson et al, 2011, 2013), wrists (e.g. Pain et al, 2013, 2015, Adams, 2016) and heads (Kleiven, 2002, 2006, Petrone et al, 2010, Samaka et al, 2013, Taha et al, 2013, Smith et al, 2015, Awad et al, 2015, Hassan et al, 2015, Antona-Makoshi, 2016, Koptyug et al, 2017). But although significant advances are reached in mathematical modelling there are certain issues related to it. First of all, any model is to some extent simplifying the reality. It is both strength of the modelling process, but in some cases it may be a weakness: too many details can mask certain key features; too little details- and we can miss or misinterpret significant ones. Another problem is that modelling demands exact input parameters, which we often either do not know exactly or they are changing depending on some conditions. For example, in typical cases of discussed modelling mechanical properties of human tissues are needed. Unfortunately, some of these are not known at all, some are hard to measure, some are nonlinear and their values depend on multiple parameters. On the top of that, mathematical models for such objects as body parts are extremely complex, and in many cases there is no guarantee that they are actually correct. Depending on the models one cannot experimentally test in designing safety equipment is at least questionable, and here physical modelling is coming into play. For example, one can model animal bones mathematically, and perform laboratory experiments breaking them. By comparing the results one can adjust the models making them better (Taha et al, 2013, Awad et al, 2015, Hassan et al, 2015, Koptyug et al, 2017). But the problem of not exactly known (or dynamically changing) input parameters still to some extent will remain with such tests. Situation changes if we can make “surrogate” body parts made of the synthetic materials with known properties (with the parameters “close to the ones of originals”) basing on the exact geometry retrieved from the real scans (Payne et al, 2013, Awad et al, 2015, Adams et al, 2016, Koptyug et al, 2017). Additive manufacturing today easily produces the real size “surrogates” of the bones replicating them in high precision. It can also produce various moulds used for casting and exact replication of the softer tissue shapes. Thus quite complex realistic physical models of the body parts are becoming available today. We can use such surrogates in experiments, comparing the results to the ones from mathematical modelling. Obviously, it



(a) **(b)** **(c)** **(d)**

Figure 4: Surrogate human head with embedded sensors for studying dynamics of the collisions: assembled head on the hybrid III neck without (a) and with (b) the "soft tissue" in place; mould with partly cast surrogate brain showing sensors placed in the plane coming through CG point (c); head-neck assembly in the helmet mounted on the impact rig.

is safe to "abuse" surrogate body parts without any risk to humans. Also, the input parameters for mathematical modelling will be now exactly known (or directly measured); geometry will follow actual body parts and will be exactly transferred into the model, allowing validating and adjusting our models and modelling approaches.

Modelling in head injury prevention is used in similar way (Awad et al, 2015, Koptyug et al, 2017). Significant improvements in the protection helmet design are already in place as a direct result of better understanding how certain impacts can affect the brain. For example, patented MIPS technology (MIPS AB, 2017) already implemented in many helmets, allows to additionally protecting from the non-central impacts leading to the rotational motions of the brain and its parts in the cranium and consequent damage to the axons. But physical modelling in this research helps to go one step further. Subjecting the surrogate body parts to excessive loading and monitoring at the results of the "injuries" does not bring the full understanding on how the damage have happened. Embedding multiple sensors into such surrogates and reconstructing the dynamics of the events during surrogate head impacts brings more precise information (Taha et al, 2013, Awad et al, 2015, Hassan et al, 2015, Koptyug et al, 2017). Now it also becomes possible to correlate the values measured by wearable sensors placed outside the "head" to what is happening inside it, adding more validity tothe empirical criteria used by multiple monitoring devices used in modern sports and training.

An advanced head surrogate with multiple embed sensors is developed at Mid Sweden University for studying concussion mechanisms and ways of better head protection (Fig. 4). It consists of the anatomically correct scull additively manufactured from the ABS polymer (Fig. 4a) surrounded by the surrogate tissue, made from silicone rubber in additively manufactured mould (Fig. 4b). Scull hosts a surrogate brain, made from soft silicone rubber cast in additively manufactured mould. Scull with the brain inside is filled with silicone oil, a surrogate of cerebral fluid. Scull, tissue and brain surrogates were designed basing on medical 3D scans. Surrogate brain was made in sequential steps, allowing sensor embedding at specific positions (Fig. 3c). Two three-axial accelerometer chips are embedded in the top part of the brain lobes, three- in the plane coming through the centre of gravity (CG) plane of the brain (Fig. 4c), and three- in the medial plane of the cerebellum ("small brain"). Additional three-axis gyroscope chip is positioned at the CG point, to monitor the motion of the brain surrogate together with acceleration sensors. Seven pressure sensors are placed across the scull at different positions to monitor changes in the surrogate cerebral fluid during the impact. Materials were selected to have properties as close as possible to the "natural" parts of human anatomy.

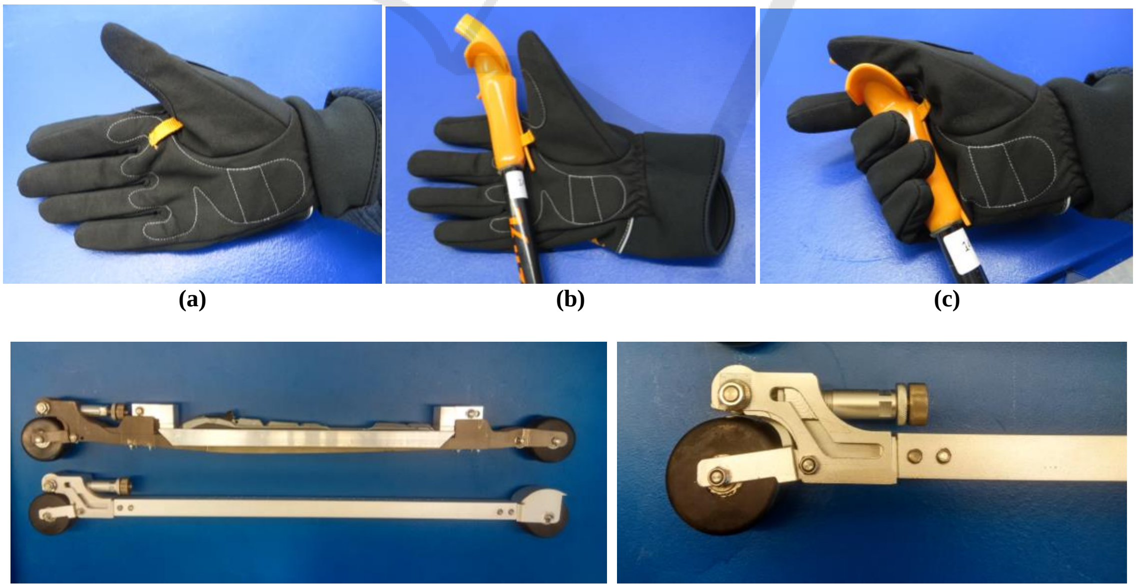
Preliminary impact tests carried out using home-made pendulum type rig (Fig. 3c) indicate that chosen sensors allow monitoring relative brain motion in the cranium under impact with a millisecond time resolution, and pressure sensors can simultaneously monitor the dynamics of the cerebral fluid pressure at different locations. Large amount of data acquired in these experiments is still analyzed, but qualitative analysis already confirms that significant rotational motion of the brain as a whole caused by non-central impacts to the head can cause significant strain in the axons of the brain stem. Non-central impacts to the head or head protection can also cause different movements of the brain lobes, and rotation of the cerebellum, which also can present certain danger for brain tissue damage. At the moment new improved version of the surrogate head model is under development.

5 TECHNOLOGY

Within the diversity of additive manufacturing applications for sports and active lifestyle we will only discuss two examples related to the prototyping and manufacturing of experimental equipment. It is clear, that such advantages of the AM and design for AM as ease of construction alterations, “virtual tests” of mechanical properties and functionality, possibility of cost-effective manufacturing polymer and metallic components of extremely complex shapes not available with other manufacturing methods, brings significant benefits for research and development work in multiple application areas. Extra dimension is added here by the possibilities of designing construction elements with embedded sensors (strain gauges, force and pressure sensors, accelerometers, gyros etc.) purpose-designed or substituting original elements of the existing construction.

Prototyping is a major part of experimental development of the devices and components based on new ideas. It is also a critical stage of product development process in industry. Flexibility, fast manufacturing of test components implementing design changes with relatively low cost processes makes additive manufacturing an ideal support tool for innovative development. One of the examples demonstrating such process in action is the development of novel ski pole handles done initially as a project within the Mid Sweden University research environment and later turned into successful commercial product (Kuzmin Ski Technology AB, 2017). Measurements performed during the World Cup biathlon event held in Östersund indicated that one of the factors slowing the athlete’s progress through the race is excessive time spent for taking off ski poles at the shooting station and putting them back on again. So ideas for the new ski pole handles for better grip and faster mounting-dismounting were put forward. Tens of prototypes in ABS polymer were designed, additively manufactured and tested in the lab and in the field. Final design (Fig. 5a-c) incorporates few innovations, including the pen-like clip on the ski pole handle and added loop on the inner side of the glove for fast “connection”, and better positioning of the thumb over the ski pole top providing better grip and power transfer in active poling.

Another typical example is development of the new roller ski design, initially done as a part of the research project and later turned into a patented


(a) (b) (c)

(d) (e)

Figure 5: Novel design of a ski pole handle: (a) additional loop added to the glove, (b) pencil-like clip is inserted into the glove loop, (c) thump positioning on the pole handle support element; novel roller ski design: (d) test version with embedded load cells (d, top) and final version (d, bottom), friction mechanism with slip adjustment (e).

product (Tinnsten et al, 2010, Ainegren et al, 2012, 2013). Many of active skiers complained that training in summer using roller skis presumes very different patterns of motion and leg muscle activity as compared to training in winter (Ainegren et al, 2012, 2013). Cross country skis used in winter have a camber: free gliding happens with only front and rear of the ski running surface having the contact with the snow, and these parts of the ski are covered with so-called “gliding wax”. To push back in classic style skiing athlete needs to load the skis forcing the central part covered with the “grip wax” getting in contact with the snow. To push back with traditional roller ski having a ratchet mechanism on the rollers one only needs backward sliding motion. Also, with the “winter skis” pushback action happens with partial slipping depending on the loading pressure, particular wax type, snow conditions, ambient temperature and humidity etc. With the ratcheted roller skis there is almost no pushback slipping, as the friction between the rubber roller and road surface is quite high. Two types of prototype roller skis were manufactured using AM technology: research ones with embedded load cells for measurement forces involved, and the ones with pushback slip action (Fig 5 d-f). New roller skis also need to be loaded like the “winter” for pushing back, and the pushback friction (extent of slipping) can also be adjusted. Extensive tests performed in the laboratory conditions and in the field indicate that roller skis of new design much better represent winter skiing, and feedback given by athletes using them is very positive.

6 SOME CONCLUSIONS

Some conclusions can already be drawn from our experiences of using additive manufacturing in education and research related to sports technology and active lifestyle. Additive manufacturing can be successfully used as one of the powerful support tools enabling the applications not available before, speeding up development processes in many different application areas, and even saving lives. Possibility to utilize significant competitive advantages of modern AM strongly depend on the knowledge of corresponding technologies, their strong points and limitations, and on practice of designing for AM. Thus incorporating additive manufacturing into the study programs for all engineering specialists, including the ones specializing in sports and active lifestyle related subjects is quite important. Involvement with additive manufacturing also helps specialists to be more innovative, to rethink old design paradigms in a novel way, to develop new research setups and methodologies and to design new products. We believe that the penetration of additive manufacturing into applications related to sports technology and active lifestyle will dramatically increase in the years to come.

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REFERENCES

Adams, C., James, D., Seniora, T., Allen, T. and Hamilton, N. (2016). Development of a method for measuring quasi-static stiffness of snowboard wrist protectors. *Procedia Engineering*, 147, pp. 378 – 383.

Ainegren, M., Carlsson, P., Laaksonen, M. and Tinnsten M. (2012). The influence of grip on oxygen consumption and leg forces when using classical style roller skis. *Scand J Med Sci Sports*, 24(2), pp. 301-310.

Ainegren, M., Carlsson, P. and Tinnsten, M. (2013).An experimental study to compare the grip of classical style roller skis with on-snow skiing. *Sports Engineering*, 16(2), pp. 115-122.

Antona-Makoshi, J. (2016). Traumatic Brain Injuries: Animal Experiments and Numerical Simulations to Support the Development of a Brain Injury Criterion. Doctoral Thesis, Chalmers University of Technology, Gothenburg, Sweden. Download available at: http://publications.lib.chalmers.se/records/fulltext/235126/235126.pdf

Awad, N., El-Dakhakhni, W. and Gilani, A. (2015). A Physical Head and Neck Surrogate Model to Investigate Blast-Induced Mild Traumatic Brain Injury. *Arab J Sci Eng.*, 40, pp. 945-958. doi:10.1007/s13369-015-1583-3

Bibb, R. Eggbeer, D. and Paterson, A. (2014). *Medical Modelling: The Application of Advanced Design and*

Rapid Prototyping Techniques in Medicine. Woodhead Publishing, 516 pages.

Bäckström, M., Tinnsten, M., Koptyug, A., Rännar, L.-E., Carlsson, P., Danvind, J. and Wiklund, H. (2013). Sports technology education at Mid Sweden University. *Procedia Engineering;* 60, pp. 214-219 .

Bäckström, M., Rännar, L.-E. and Koptyug, A. (2012). Spare Parts for Human Body. *Science First Hand;* 2(44) pp. 44-57. File download available at: https://www.researchgate.net/publication/313367815_Spare_Parts_for_Human_Body

Christensen, A., Lippincott, A. and Kircher, R. (2007). An Introduction to Electron Beam Melting with Ti6Al4V-ELI for the Orthopaedic Device Industry. *BONEZone*; 6, pp 14-17.

Chudinova, E., Surmeneva, M., Koptioug, A., Skoglund, P. and Surmenev, R. (2016). Additive manufactured Ti6Al4V scaffolds with the RF-magnetron sputter deposited hydroxyapatite coating. *Journal of Physics: Conference Series*; 669, 012004.

Cronskär, M., Rännar, L.-E., Bäckström, M. and Koptyug, A. (2008). Application of electron beam melting to titanium hip stem implants. *In: Proc Intl Conference on Additive Technologies, Vienna, DAAAM International*; p. 1559.

Cronskär, M., Rännar, L.-E. and Bäckström, M. (2012). Implementation of Digital Design and Solid Free-Form Fabrication for Customization of Implants in Trauma Orthopaedics. *Journal of Medical and Biological Engineering;* 32(2), pp. 91-96.

Cronskär, M., Bäckström, M. and Rännar, L.-E. (2013). Production of customized hip stem prostheses – a comparison between conventional machining and electron beam melting (EBM). *Rapid Prototyping Journal*; 19(5), pp.365-372.

Cronskär, M. and Bäckström M. (2013). Modeling of fractured clavicles and reconstruction plates using CAD, finite element analysis and real musculoskeletal forces input. *WIT Transactions on Biomedicine and Health*; 17, pp. 235 - 243.

Cronskär, M. (2014). Mid Sweden University Doctoral Thesis 191: On customization of orthopedic implants - from design and additive manufacturing to implementation. Mid Sweden University, Sweden http://miun.diva-portal.org/smash/get/diva2:745912/FULLTEXT01.pdf

Emerson, N., Carré, M., Reilly, G. and Offiah, A. (2011). Geometrically accurate 3D FE models from medical scans created to analyse the causes of sports injuries. *Procedia Engineering*; 13, pp. 422-427.

Emerson, N., Carré, M., Reilly, G. and Offiah, A. (2013). Simulation based upon medical data offers a fast and robust method for the prediction of fracture risk. *Procedia Engineering*; 60, pp.459 – 466.

Emerson, .N., Offiah, A., Reilly, G. and Carré, M. (2013). Patient-specific finite element modelling and validation of porcine femora in torsion. *Strain*; 49 (3), pp. 212-220.

Fera, M., Fruggiero, F., Lambiase, A. and Macchiaroli, R. (2916). State of the art of additive manufacturing: Review for tolerances, mechanical resistance and production costs. *Cogent Engineering*; 3: 1261503, 16 pages.

Ganesan, B., Al-Jumaily, A. and Luximon, A. (2016). 3D Printing Technology Applications in Occupational Therapy. *Phys Med Rehabil Int*.; 3(3), pp. 1085-1088.

Hassan, M.H.A. and Taha, Z. (2015). Finite Element Analysis of Soccer Heading. *Procedia Engineering*, 112, pp. 46–51.

Heinl, P., Müller, L., Körnera, C., Singera, R. and Müller, F. (2008). Cellular Ti–6Al–4V structures with interconnected macro porosity for bone implants fabricated by selective electron beam melting. *Acta Biomaterialia*; 4(5), pp. 1536–1544.

Helene Ripa (2017), https://en.wikipedia.org/wiki/Helene_Ripa

Huiskes, R., Weinans, H. and van Rietbergen B. (1992). The relationship between stress shielding and bone resorption around total hip stems and the effects of flexible materials. *Clin Orthop Relat Res*.; 274, pp.124-34.

IPC regulations on Nordik Skiing, https://www.paralympic.org/nordic-skiing/rules-and-regulations

Jina, Y., Plotta, J., Chena, R., Wensmanc, J. and Shih, A. (2015). Additive Manufacturing of Custom Orthoses and Prostheses – A Review. *Procedia CIRP*; 3,6 pp. 199 – 204. Available online at http://www.sciencedirect.com

Kleiven, S. and Hardy, W. (2002). Correlation of an FE Model of the Human Head with Local Brain Motion – Consequences for Injury Prediction. Stapp Car Crash Journal, 46, pp. 123-144.

Kleiven, S. (2006). Evaluation of head injury criteria using a finite element model validated gainst experiments on localized brain motion, intracerebral acceleration, and intracranial ressure

International Journal of Crashworthiness, 11(1), pp 65-79.

Koptyug, A., Rännar, L.-E., Bäckström, M. and Klingvall, R. (2012). Electron Beam Melting: Moving from Macro- to Micro- and Nanoscale. *Materials Science Forum*; 706-709, pp. 532-537.

Koptyug, A., Rännar, L.-E., Bäckström, M., Franzén, S. and Dérand, P. (2013). Additive Manufacturing Technology Applications Targeting Practical Surgery. *Int. J. Life Science and Medical Research*; 3(1), pp.15-24.

Koptyug, A., Rännar, L.-E., Bäckström, M. and Langlet, A. (2013). Bulk Metallic Glass Manufacturing Using Electron Beam Melting. *In: Proc. International Conference on Additive Manufacturing & 3D Printing, Nottingham*; July 9-10

Koptyug, A., Bergemann, K., Lange, R., Jaggi, V.-E., Rännar, L.-E. and Nebe B. (2014). Osteoblast Ingrowth into Titanium Scaffolds made by Electron Beam Melting. *Materials Science Forum*; 783-786, pp. 1292-1297.

Koptyug, A., Rännar, L.-E., Bäckström, M. and Cronskär, M. (2014). Additive Manufacturing for Medical and Biomedical Applications: Advances and Challenges. *Materials Science Forum;* 783-786, pp.1286-1291.

Koptyug, A., Rännar, L.-E., Bäckström, M. and Surmenev, R. (2017). Additive manufacturing in metal: advances generate new research challenges. *Nanotehnology: development and applications in XXI century*; 8(4), pp. 12-36.

Koptyug, A., Rännar, L.-E., Bäckström, M. and Shen, Z. (2017). New metallurgy of Additive Manufacturing in Metal: Experiences from the Material and Process Development with Electron Beam Melting Technology (EBM). *Materials Science Forum;* 879, pp. 996-1001.

Koptyug, A., Bäckström, M. and Petrone, N. (2017). Developing an Instrumented Physical Model of the Human Head for Studying Concussion Mechanisms. *Proc. 22nd Congress of the International Society for Skiing Safety*, Innsbruck, April, 17 – 22 2017, p. 81.

Kuzmin Ski Technology AB (2017)
http://www.kuzmin.se/pgs/skiing_en.html

MakerBot Industries, LLC (2017) https://www.makerbot.com/products/3d-printers/

Mills, D. (2015). Future Medicine: The Impact of 3D Printing. *J Nanomater Mol Nanotechnol* 4:3.

MIPS AB, http://www.mipsprotection.com/

Murr, L,. Gaytan, S., Medina, F., Lopez, H., Martinez, E., Machado, B., Hernandez, H., Martinez, L., Lopez, M., Wiker, B. and Bracke, J. (2010). Next-generation biomedical implants using additive manufacturing of complex, cellular and functional mesh arrays", *Phil. Trans. Roy. Soc. A*; 368, pp. 1999-2032.

Niinomi, M. and Nakai, M. (2011). Titanium-Based Biomaterials for Preventing Stress Shielding between Implant Devices and Bone. *Intl. J. Biomater.*; 2011, Article ID 836587.

Pallis, J. *Materials in Paralympic Sports*. Chapter 14, in: Materials in Sports Equipment, Volume 1. Ed. Mike Jenkins, Elsevier, 2003 - Technology & Engineering - 424 pages

Palousek, D., Rosicky, J., Koutny, D., Stoklasek, P. and Navrat, T. (2014). Pilot study of the wrist orthosis design process. *Rapid Prototyping Journal*; 20(1), pp. 27-32.

Pauly, S., Löber, L., Petters, R., Stoica, M., Scudino, S., Kühn, U., and Eckert J. (2013). Processing metallic glasses by selective laser melting. *Materials Today*; 1(1-2), pp. 37-41.

Payne, T., Mitchell, S. and Bibb, R. (2013). Design of human surrogates for the study of biomechanical injury: a review. *Critical Reviews in Biomedical Engineering*; 41 (1), pp. 51-89.

Payne, T., Mitchell, S., Halkon, B.; Bibb, R. and Waters, M. (2015). Development of novel synthetic muscle tissues for sports impact surrogates. *J. Mechanical Behavior of Biomedical Materials*; 41, pp. 357-374.

Petrone, N., Tamburlin, L., Panizzolo, F. and Atzori, B. (2010). Development of an instrumented anthropomorphic dummy for the study of impacts and falls in skiing. Procedia Engineering, 2(2), pp.2587-2592.

Samaka, H. and Tarlochan, F. (2013). Finite Element (FE) Human Head Models / Literature Review. *Intern. J. of Sci. Tech. Research*, 2(7), pp. 17-21.

Sames, W., List, F., Pannala, S., Dehoff, R and Babu, S. (2016). The metallurgy and processing science of metal additive manufacturing. *International Materials Reviews*; 6 (5), pp. 315-360.

Skoglund, P. (2915). Prosthetic socket in Titanium, Mid Sweden University Master Thesis. Download available at: https://www.diva-portal.org/smash/get/diva2:901421/FULLTEXT01.pdf

Smith, T., Halstead, P., McCalley, E., Kebschull, S., Halstead, S. and Killeffer, J. (2015) Angular head motion with and without head contact: implications for brain injury. *Sports Engineering*, 18(3), pp. 165-175.

Special issue: Technology for Disability Sport. (2016). *Sports Engineering*; 9(3); Eds. Koptyug, A., Burkett, D. pp 139.

Stratasys Ltd. (2017) http://www.stratasys.com/3d-printers

Sumner, D. (2015). Long-term implant fixation and stress-shielding in total hip replacement. *J Biomech*.; 48(5), pp. 797-800.

Surmenev, R., Surmeneva, M. and Ivanova, A. (2014). Significance of calcium phosphate coatings for the enhancement of new bone osteogenesis–A review. *Acta biomaterialia;* 10 (2), pp. 557-579.

Surmeneva, M., Chudinova, E., Syrtanov, M., Koptyug, A. and Surmenev, M. (2015). Investigation of the HA film Deposited on the Porous Ti6Al4V Alloy Prepared via Additive Manufacturing. *IOP Conference Series: Material Science and Engineering*; 98, 012025.

Taha, Z., Hassan, M., Aris, M. and Anuar, Z. (2013). Predicting brain acceleration during heading of soccer ball. *IOP Conf. Series: Materials Science and Engineering*, 50(1), 012023.

Tinnsten, M., Peter Carlsson, P., Ainegren, M., and Sandberg, S. (2010). Arrangement for a roller ski and a roller ski. European patent EP 2418006.

Zadpoor, A. and Malda, J. (2917). Additive Manufacturing of Biomaterials, Tissues, and Organs. *Annals of Biomedical Engineering*; 45(1), pp. 1–1.

Zhong, Y., Rännar, L.-E., Liu, L., Koptyug, A., Wikman, S., Olsén, J., Cui, D. and Shen, Z. (2017) Additive manufacturing of 316L stainless steel by electron beam melting for nuclear fusion applications. *Journal of Nuclear Materials*; 486, pp. 234-245.

Zhong, Y., Rännar, L.-E., Wikman, S., Koptyug, A., Liua, L., Cui, D. and Shen, Z. (2017). Additive manufacturing of ITER first wall panel parts by two approaches: Selective laser melting and electron beam melting. *Fusion Engineering and Design;* 116, pp. 24–33.