Is Additive Manufacturing Improving Performance in Sports? A Systematic Review

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Is Additive Manufacturing Improving Performance in Sports? A Systematic Review

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Abstract

Sport is an industry that may benefit from the opportunities offered by Additive Manufacturing (AM), and the media has portrayed increasing adoption of the technology in sports products. This systematic review aimed to consolidate and interpret the available empirical evidence concerning applications of AM in sports following the Preferred Reporting Items for Systematic Review and Meta-Analysis Protocols (PRISMA-P) 2015. Four databases were searched within the date range of January 1984 to May 2019, using twenty-eight broad and specific search phrases. This resulted in twenty-six articles for analysis, the first appearing in 2010. Twelve sports in total were identified across the literature, with running/walking the most popular sport with ten articles (38%) investigating AM, followed by cycling with four articles (15%) and badminton with three articles (12%). Ten articles (38%) observed improvements in performance of products developed via AM compared to conventionally manufactured products, eight articles (31%) found a similar performance, and five articles (19%) found a lower performance. From a technical perspective, powder bed fusion technologies were the most utilized with 50% of articles using either selective laser sintering (SLS) or selective laser melting (SLM), although 52% of articles did not name the 3D printer used and 36% did not name any software used to design or optimize products. 3D scanning technology was also utilized within eleven (42%) articles. Results indicate that AM has been slow to permeate sports research, and while considered across a variety of potential applications, has largely resulted in singular studies with potentially limited opportunities or funding for follow-up investigations.

Keywords: 3D printing, 3D scanning, literature review, performance, PRISMA-P, product design, sport technology

Introduction

Additive manufacturing (AM), synonymously known as three-dimensional (3D) printing,[1] has emerged over the last decade as a transformative technology across many manufacturing sectors, from advanced aerospace and medical applications through to more personalized applications in fashion and product design. This industry is estimated to be worth US$15.8 billion in 2020, forecast to more than double to US$35.6 billion in 2024.[2] The transition from a rapid prototyping technology to one capable of producing functional end-use parts has seen AM become mainstream within some industries.[3-5] For example, the production of in-ear hearing aids largely shifted to additive processes between 2000-2006 for all major manufacturers,[6] more than 60,000 acetabular cups fabricated using electron beam melting were implanted in patients by 2017,[7] and GE Additive and Boeing currently manufacture tens of thousands of aircraft components annually using both polymer and metal 3D printing.[8] Industries like transport (e.g. aerospace and automotive), medical (e.g. dental and implants), toys and jewelry have been shown to have the highest utilization of AM technology,[9,10] supported by strong academic research particularly within transport and medicine. The increasing adoption of AM in these industries is primarily due to the inherent opportunities for customization, weight reduction, and iterative experimentation in low volumes.[5, 9, 11, 12]

Sport is also an industry that is logically suited to the opportunities offered by AM and is frequently mentioned in AM academic literature.[5, 9, 11, 12] Sporting products are typically mass-produced to suit normative populations e.g. typical athlete heights, weights, foot sizes and limb lengths. As such, products like customized orthotic insoles are often made available to help adjust standard shoes to fit individual anatomies more appropriately, however, in many cases, these "customized" products are also produced in a limited range of sizes and shapes or must be manipulated in a post-hoc fashion via processes like heat molding. Comparatively, AM offers the opportunity to produce truly customized products that fit individual anatomies and performance requirements exactly, thus having potential to improve comfort, mitigate injuries (particularly overuse injuries) and improve performance.

Despite the opportunities, research into the use of AM in sports is limited. Therefore, it is difficult to ascertain whether these theoretical benefits could be realized in practice. Notably, in the limited existing sports AM research, products are rarely supported with detailed case studies or data, with Mawale et al. describing that the sports industry is only at the "initiating phase" of adoption.[9] A 2019 study of awareness of AM within the sports industry by Meier et al.[10] suggested limitations such as a lack of functional materials, lack of expertise in designing products for AM and high machine costs remain challenges, despite evidence from other industries of increasing adoption. Furthermore, the study found through literature review and interviews with industry leaders that the sports industry has a general lack of awareness of AM technology, and while the technology is helping to drive innovation in product design, particularly through rapid prototyping (a term used to describe the application of AM technologies for producing prototypes rather than end-use products[1]), it is not being implemented in any significant way to drive production of new forms of products and markets.

Contrastingly, online media portrays a different story with sporting applications of 3D printing gaining significant coverage in recent years, including shoes by Nike (e.g. Flyknit[13]), Adidas (e.g. Futurecraft 4D[14]) and New Balance (e.g. Zante Generate[15]), as well as shin pads,[16] bicycles,[17, 18] helmets,[19, 20] Olympic speed skating gloves,[21] prosthetics used in the Paralympics[22] and countless other examples. Carbon (Redwood City, California, USA), creators of Continuous Liquid Interface Production (CLIP) technology, have collaboratively developed three high-profile sports products with leading manufacturers which are currently available to consumers, or planned in the near future: the

Adidas Futurecraft 4D shoes,[14] a customizable football helmet liner for Riddell Sports Group[23] (Des Plaines, IL, USA) and a bicycle saddle called the S-Works Power Saddle for Specialized (Specialized Bicycle Components, Morgan Hill, CA, USA) featuring a lattice structure made up of over 14,000 struts.[24] While these examples may be the exception within the sports industry for adoption of AM, rather than the rule, their prominence online and growing consumer awareness does portray an increasing adoption for its ability to offer new performance-driven qualities to the market.

Due to the pace of AM innovation, information about new shoes and other products produced through AM are often only available through mainstream news websites and company media releases, rather than more traditional academic sources. This challenge has been acknowledged particularly within formal AM education, with flipped classroom models and project-based learning encouraging the use of various digital resources to inform learning that is current and aligned with industry.[25-27] Given these contrasting portrayals of AM within sports, this study asked the question *what scientific evidence is available that AM provides improved sporting products?* The main objectives were to document the types of sports and products utilizing AM, identify the different AM technologies, materials, software and associated digital technologies employed, document the scale of research studies, and synthesize the opportunities and challenges of AM from literature. It was hypothesized that if AM technology is being used to manufacture end-use sporting products for some of the most iconic global brands, then there should be a growing volume of scientific evidence supporting claims of improved performance, comfort or other properties.

To answer this question, a systematic review methodology was employed. Through meta-analysis, this provided an overview of trends related to sporting applications of AM, as well as technical knowledge related to hardware and software used within research. The study provides a roadmap of sports-related AM research since the technology emerged, allowing researchers to understand the current state of the field, and provides direction for future research based on this understanding. Whether AM is supported by researchers, or simply media hype that inflates consumer expectations, this study provides an objective analysis of academic research into sporting applications as the technology transitions from rapid prototyping to increasingly end-use applications.

Method

This systematic review and meta-analysis was conducted according to the Preferred Reporting Items for Systematic Review and Meta-Analysis Protocols (PRISMA-P) 2015.[28] The review was conducted across ProQuest, Scopus, Web of Science and SPORTDiscus databases between 17-21 May 2019, with results of each search saved directly to an Endnote library for further analysis. Search results were limited to those published between January 1984 and May 2019 when the search was conducted, with the year 1984 chosen to coincide with the first patents for AM technology filed in Japan, France and the United States of America.[3] Endnote was chosen for this review process due to the availability of the software, resources, and experience of both authors using the advanced features, as well as the ability to easily share and combine libraries between both authors for the review process.

The terms *3D printing*, *additive manufacturing* and *rapid prototyping* have often been used interchangeably to describe the technology.[1] Therefore, literature searches included each of these terms in order to capture all relevant publications. This is evidenced in Table 1 which details all searches conducted within each database for this systematic review. Where possible in the search functions of the four databases, searches were restricted to articles that were peer reviewed and written in the English language. Table 1 also shows sports that are similar with results later combined, specifically running/walk*, cycling/bicycl*, soccer/football.

Table 1. Searches conducted in each database, with grayscale used to group similar sports/searches.

Search Phrase	Search Location
("rapid prototyp*" OR "3d print*" OR "additive manufactur*") AND cycling	Title, abstract, keywords
("rapid prototyp*" OR "3d print*" OR "additive manufactur*") AND danc*	
("rapid prototyp*" OR "3d print*" OR "additive manufactur*") AND running	
("rapid prototyp*" OR "3d print*" OR "additive manufactur*") AND swim*	
("rapid prototyp*" OR "3d print*" OR "additive manufactur*") AND walk*	
("rapid prototyp*" OR "3d print*" OR "additive manufactur*") AND athletic*	Anywhere within the text of an article
("rapid prototyp*" OR "3d print*" OR "additive manufactur*") AND badminton	
("rapid prototyp*" OR "3d print*" OR "additive manufactur*") AND baseball	
("rapid prototyp*" OR "3d print*" OR "additive manufactur*") AND basketball	
("rapid prototyp*" OR "3d print*" OR "additive manufactur*") AND bicycl*	
("rapid prototyp*" OR "3d print*" OR "additive manufactur*") AND cricket*	
("rapid prototyp*" OR "3d print*" OR "additive manufactur*") AND football	
("rapid prototyp*" OR "3d print*" OR "additive manufactur*") AND golf*	
("rapid prototyp*" OR "3d print*" OR "additive manufactur*") AND gymnastic*	
("rapid prototyp*" OR "3d print*" OR "additive manufactur*") AND hiking	
("rapid prototyp*" OR "3d print*" OR "additive manufactur*") AND hockey	
("rapid prototyp*" OR "3d print*" OR "additive manufactur*") AND "martial art*"	
("rapid prototyp*" OR "3d print*" OR "additive manufactur*") AND netball	
("rapid prototyp*" OR "3d print*" OR "additive manufactur*") AND "resistance training"	
("rapid prototyp*" OR "3d print*" OR "additive manufactur*") AND rugby	
("rapid prototyp*" OR "3d print*" OR "additive manufactur*") AND soccer	
("rapid prototyp*" OR "3d print*" OR "additive manufactur*") AND sport*	
("rapid prototyp*" OR "3d print*" OR "additive manufactur*") AND "stair climb*"	
("rapid prototyp*" OR "3d print*" OR "additive manufactur*") AND "table tennis"	
("rapid prototyp*" OR "3d print*" OR "additive manufactur*") AND "tai chi"	
("rapid prototyp*" OR "3d print*" OR "additive manufactur*") AND tennis	
("rapid prototyp*" OR "3d print*" OR "additive manufactur*") AND volleyball	
("rapid prototyp*" OR "3d print*" OR "additive manufactur*") AND yoga	

The keyword "sport" was used as one of the searches to capture relevant literature which may have spanned multiple sports or contained non-specific titles. To further capture as much relevant literature as possible, the top ten adult sports across six regions of the world were identified from a systematic review by Hulteen et al.,[29] and separately searched within each database. These sports align with statistics from other reports about popular sports,[30-32] yet an acknowledgement must be made that not every sport in the world could be reasonably searched for this study. Modifications to search keywords from the Hulteen et al.[29] study included the use of both *football* and *soccer* which are used in different regions of the world to describe the same sport, as well as the additional search for *bicycle* alongside *cycling* due to the prominence of bicycles as both sporting and recreational products that may be discussed in literature isolated from discussions of the activity of cycling. Running and walking results were also combined due to the similarities in equipment and techniques for these sports, which may also be considered recreational activities.[30] This resulted in twenty-eight separate searches within each database and comprised of twenty-four distinct sports when running/walking, cycling/bicycle and soccer/football were combined.

Due to "walking" and "running," as well as "cycling," "swimming" and "dancing" also being verbs used to describe other events (e.g. power *cycling* a computer, or *walking* a jury through a crime scene), limitations were placed on these five searches to results appearing only in the title, keywords or abstract (aka. no full text), whereas all other searches were conducted anywhere within the full-text of an article. Sports with motors were also excluded from this study, for example Formula One and MotoGP, as they were not featured in literature as the most popular sports[29-32] and their relationship with research to various automotive disciplines would be difficult to separate from research relevant to sporting applications.

After gathering initial search results, duplicates were removed using automatic tools within Endnote. Further duplicates were manually removed from the library in circumstances where different databases classified the same article differently (e.g. conference paper or conference proceeding), or where information was slightly different (e.g. author first and last names in the wrong order). This complete library of results was then independently screened by both authors, assessing article titles and abstracts against inclusion criteria:

1. The article must use AM to produce a functional piece of sporting equipment. This excludes instances of AM used to create prototypes as part of the design process, or studies that focused exclusively on digital simulation (e.g. Finite Element Analysis) of a product design that was intended for AM at a future time.
2. The article must provide quantitative data about the designed product.
3. The equipment must be used during typical sporting activities i.e. training or match play. Supporting products that were medical/rehabilitative in nature were excluded.
4. The article must be original. Review papers that report findings from other studies were excluded.

Articles meeting inclusion criteria by the authors were then combined into a single library and remaining articles were read in full to assess final validity for inclusion. These articles were accessed through the institution libraries of the authors, or where access was restricted, through online repositories of papers and preprints like ResearchGate and academia. Where this was not possible, authors of papers were directly contacted. Papers retained after the full-text review were analyzed in detail using an evidence table to report relevant study characteristics and outcomes reported in this review.

Results

In total, 11,185 articles were identified through the search, which were reduced to 7,995 articles after removal of duplicates (using both an automated function in Endnote, followed by manual screening for duplicates). Each of the authors screened the complete list of articles using separate methods: One of the authors removed 7,791 articles through methodical screening of titles and abstracts, while the other removed 7,931 using keywords to find articles that did not meet inclusion criteria. When these results were combined (268 articles), and duplicates between the two libraries were removed (n = 49), 219 articles remained for full-text review. A further 193 articles were removed upon this review for failing to meet inclusion criteria, resulting in 26 articles that met all inclusion criteria. This process is illustrated in Figure 1.

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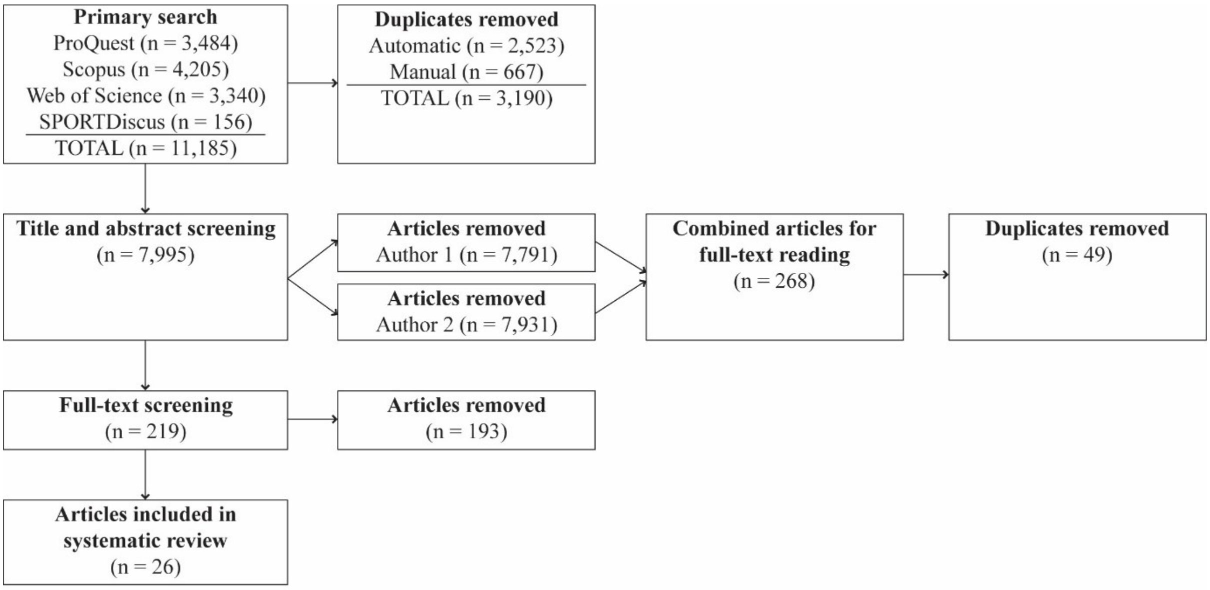

Figure 1. Strategy and results of systematic review at each stage of the process to identify relevant literature.

As shown in Figure 2, articles quantifying improvements in human performance via AM product design did not emerge in academic publications until 2010, twenty-six years after key patents were filed for the technology. In total, between January 2010 and May 2019, eighteen journal articles (69%), seven conference papers (27%) and one book chapter (4%) were published, with an average of 2.67 articles published per year (excluding the partial year 2019).

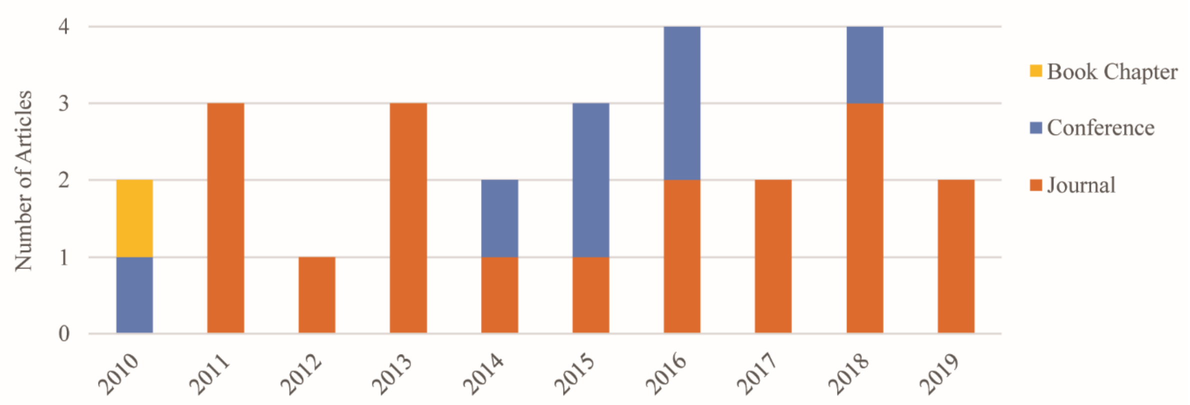

Figure 2. Type of publication by year.

Sports within literature

Figure 3 shows the sporting activities featured in the literature, with running/walking being the most popular with ten articles (38%), followed by cycling with four articles (15%) and badminton with three articles (12%). The other sports that were featured only in a single publication were: baseball, climbing, cricket, football (soccer), golf, hurling, in-line skating, rowing and surfing. It is important to note from this data that of the twenty-four discrete sports searched in databases (considering groupings in Table 1 and excluding the general term "sport*"), only eight of these sports appeared in the literature (33%). Despite sixteen other sports being listed in the top ten across different regions of the world,[29] 66% of the specific sport searches did not reveal any articles meeting inclusion criteria. However, four sports that were not specifically searched were identified in the literature: hurling, in-line skating, rowing and surfing.

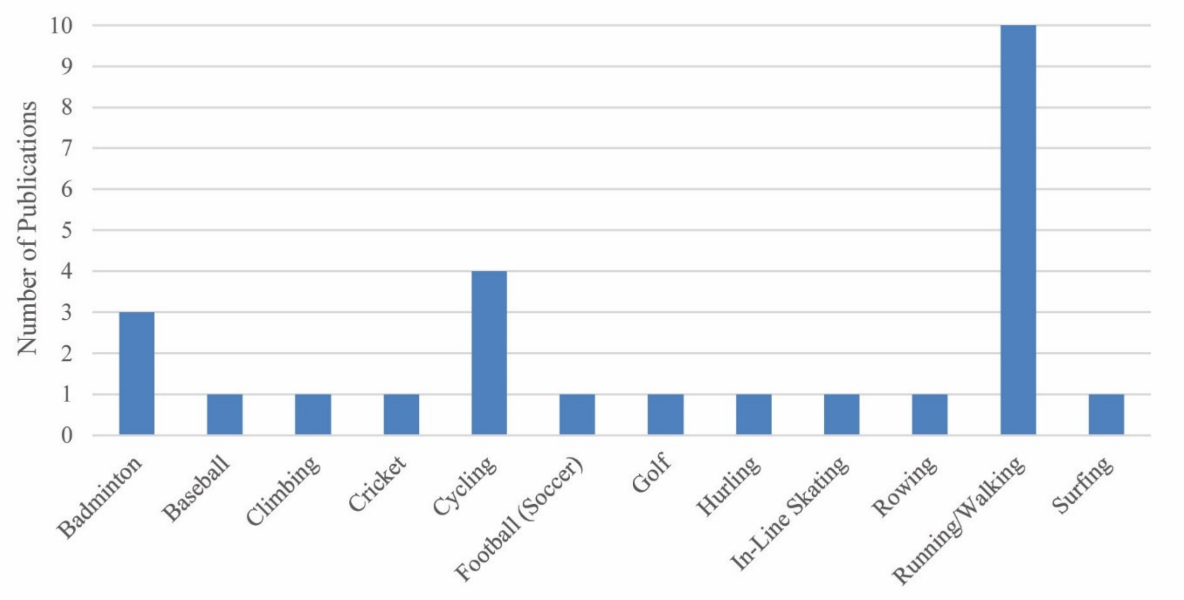

Figure 3. Sports investigated in literature.

While badminton has had three publications investigating the use of AM for shuttlecocks, these publications have been produced by the same authors between 2013-2015,[33-35] indicating that research on this topic has not extended outside of a single research group. Running/walking exhibits a similar trend, with the ten publications produced by four distinct research groups: Salles et al. are responsible for five of the publications investigating insoles,[36-40] Vinet et al. have three publications on sprint shoes,[41-43] and the remaining two publications are produced by individual research groups investigating AM of vortex generators on running apparel[44] and AM of insoles.[45] The four articles within the sport of cycling are from discrete research groups. Therefore, cycling and running/walking may be considered to have a similar interest in the application of AM with four unique research groups publishing results within the scope of this literature review. Overall, this means that the twenty-six publications were produced by eighteen unique author groups, potentially indicating limited opportunities or funding for follow-up investigations.

In order to understand the performance properties of additively manufactured sporting products compared to conventionally manufactured products, summarized results from the twenty-six publications are presented in Table 2. The final column provides a quick reference overview comparing whether the AM products provided significant improvements compared to conventional products tested (↑), similar performance (-), or lower performance (↓). Significance was determined through statistical analysis of empirical data and other qualities described within each article. Several articles did not provide comparisons to existing products (N/A),[46, 47] and one article was unable to be accessed through online databases and attempts to directly contact authors.[48] It is important to note that the criteria used to assess performance in each study is different, and making comparisons between different studies is difficult. For example, depending on the product or feature, "improving" a quality such as aerodynamic performance may be considered negative, as demonstrated in the

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badminton studies where reducing the drag coefficient of a shuttlecock would alter the flight behavior understood by players, negatively impacting play. Therefore, in badminton studies[33-35] a similar result (-) is considered positive where AM is being investigated to replace the need for waterfowl feathers.

Table 2. Summarized literature results in alphabetical order of sport then year, with overall performance comparison of AM product versus conventional product (↑-↓).

Reference	Sport	Product	Data Summary	↑-↓
[33] 2013 Journal	Badminton	Shuttle-cock	Two shuttlecocks produced with AM exhibited reduced drag compared to a commercial feather shuttlecock, while another design was able to achieve similar drag performance.	-
[34] 2014 Conference	Badminton	Shuttle-cock	Simulation and wind tunnel tests of the AM shuttlecock were similar to a feather shuttlecock at wind tunnel speeds below 15m/s. However, they varied significantly at speeds over 15m/s due to deformation of the skirt.	↓
[35] 2015 Journal	Badminton	Shuttle-cock	The AM shuttlecock had a lower drag-to-mass ratio than the reference feather shuttlecock. The results showed significant variation in the clear and smash shots due to insufficient drag on the prototype. The net shot showed good agreement with the feather shuttlecock.	↓
[46] 2016 Journal	Baseball	Leg guard	Evaluations of custom leg guards by athletes found them to be comfortable and effectively protect the legs, although no comparison was made to an existing product.	N/A
[48] 2015 Conference	Climbing	Fall arrest	Paper could not be accessed	N/A
[49] 2015 Conference	Cricket	Helmet face guard	A custom titanium face guard designed for a specific athlete was able to successfully pass load-bearing tests described by BS 7928:2013 standards.	-
[50] 2014 Journal	Cycling (Mountain)	Bicycle frame	Traditional bike frame 2100g, AM bike frame 1400g, overall 33% reduction in frame weight. 44% weight reduction in the seat post bracket. Fatigue testing of the seat post bracket: 50 000 cycles of 1200 N, achieving 6x the standard.	↑
[51] 2016 Journal	Cycling (Mountain)	Bicycle frame yoke	A titanium yoke piece produced by CNC machining weighs 136g and costs $477.50AUD. A purpose-designed part for AM has a weight of 120g (-12%) and costs $193.50AUD (-60%).	↑
[52] 2018 Journal	Cycling	Crank	Deformation of AM cranks under static loading was 7.0 ± 0.5 mm per crank, similar to 2 commercial cranks. However, the samples failed critically during fatigue testing at 2370 and 2620 cycles.	↓
[19] 2019 Journal	Cycling	Helmet	Several helmets produced with AM featured adjustable ventilation openings able to vary the overall drag experienced by a cyclist by up to 4.1% between open and closed positions. In the closed position a helmet was able to achieve drag area measurements within ~1% of a time trial Kask Bambino with visor, and within ~2% of a Giro Advantage with visor.	-
[53] 2019 Journal	Football (soccer)	Shin guard	Using a 1kg weight with metal stud dropped at a 400mm height, two AM specimens had acceleration reductions between 42% and 68% with respect to two commercial shin guards, while the penetration was reduced 13%–32%. The attenuation and the contact times were similar.	↑
[47] 2016 Conference	Golf	Golf ball	Eleven golf-balls with various dimple geometries tested in a wind tunnel found a near linear relationship between relative roughness and drag coefficient. At 100km/h, a ball with shallower dimples will travel further.	N/A
[54] 2018 Journal	Hurling	Gloves	Comfort: Only 2/9 players rated the gloves to be a good comfort level. Performance: No players indicated that the glove enhanced performance. Protection level: 1/9 a lot, 4/9 average, 2/9 a little, 2/9 none.	↓

[55] 2018 Conference	In-line Skating	Skating wheels	An in-line skating wheel has a total volume of 66,900 mm^3. A Superformula optimized wheel for AM had an average volume of 2,366 mm^3, with the best result being 1,985 mm^3, which is 2.97% of the solid wheel volume.	↑
[56] 2017 Journal	Rowing	Insole	A textured insole produced with AM provided significantly greater force and contact area at peak force and over the whole drive phase than the control insoles. In general, power slightly increased in the range of 3-11W for one of the AM insoles compared to the control, and the mean distance travelled was from 4-12m longer than that travelled with control insoles, but were not statistically significant.	↑
[36] 2010 Book Chapter	Running	Insole	During the first 1.5 months, the control insole caused discomfort in 63% of participant training sessions compared with 51% for the AM insole. In the last 1.5 months the runners in the control condition reported some discomfort in 38% of their training sessions, whereas the participants in the AM group reported discomfort in 20%.	↑
[42] 2010 Conference	Running (sprint)	Shoes	An AM sprint spike design was able to generate traction forces similar to commercially available sprint shoes tested, across the levels of normal loading examined.	-
[40] 2011 Journal	Running	Insole	As [34].	↑
[41] 2011 Journal	Running (sprint)	Shoes	AM shoe soles were able to improve performance in several tests including: maximum dynamic strength of squat jump testing (2182N compared with 1911N for the control) and ankle power (307.5W compared with 264.4W for the control), as well as results for bounce drop testing.	↑
[43] 2011 Journal	Running (sprint)	Shoes	The "needle and pin" concept sole was the best performing design, achieving 0.6% more peak traction force than the worst performing commercial shoe (Adidas) at a 500N load, however, in general the AM concept shoes generated lower mean peak static forces than the commercially available sprint shoes.	↓
[37] 2012 Journal	Running	Insole	The mean ratings for foot discomfort variables were low for both standard and AM insoles, but statistical analysis showed no significant differences between the two conditions.	-
[38] 2013 Journal	Running	Insole	As [35].	-
[39] 2013 Journal	Running	Insole	AM insoles had less reported discomfort when compared to the control for all measured aspects of the foot regions. For the heel and fit, significant differences between conditions were detected, whilst for the forefoot and midfoot the difference was approaching significance.	↑
[44] 2016 Conference	Running	Apparel	With vortex generators directly 3D printed onto race apparel, aerodynamic drag (F_d) forces were reduced between 3.7 and 6.8% compared to equivalent advanced race apparel developed for the 2012 London Olympics.	↑
[45] 2018 Journal	Running / Walking	Insole	The effects of wearing a customized 3D-printed insole was not significantly different from those of a ready-made insole regardless of walking/running speed.	-
[57] 2017 Journal	Surfing	Surf fins	The performance of a surfboard with AM fins was similar to the performance of a surfboard using commercial fins.	-

Key: ↑ = improved performance; ↓ = reduced performance; - = similar performance (may be a positive result where the intent was to achieve the same performance using different methods/materials); N/A = not applicable.

From the data in Table 2, the number of articles that found an improved performance of AM products compared to conventional products was ten (38%). Eight articles (31%) found a similar performance (which may also be considered positive depending on the study intent), five articles (19%) found a

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lower performance, and three articles (12%) did not provide comparison outside of products produced. This data is visualized in Figure 4. From the specific products investigated within the literature it is also possible to classify them into three broad categories: Equipment that is essential to the sport, including balls, bicycles and shoes (n=14, 54%), products designed to enhance comfort, fitting and/or reduce injury risk, specifically insoles (n=7, 27%), and products that provide protection such as helmets and shin guards (n=5, 19%). This is visualized in Figure 5.

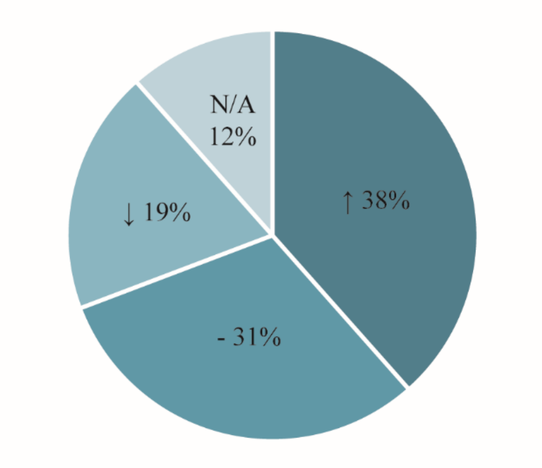

Figure 4. Overall advantage (↑), similarity (-), disadvantage (↓) between AM and conventional products summarized from Table 2. N/A denotes articles that did not provide comparison to existing products.

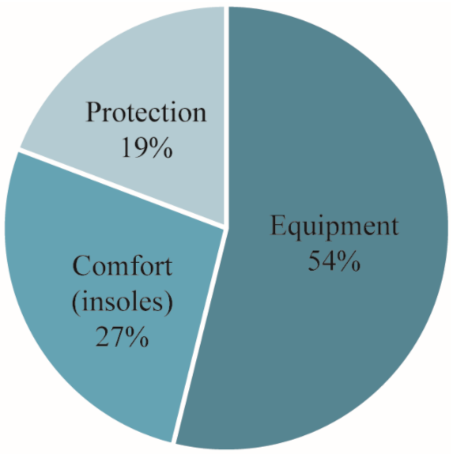

Figure 5. Categories of products within literature summarized from Table 2.

Additive Manufacturing and Associated Technologies

From a technical perspective Table 3 summarizes the CAD software, AM technologies, materials and other technologies employed in each study. The type of AM technology has been graphed in Figure 6, showing that selective laser sintering (SLS) featured in nine articles (33%), which was the most used technology, followed by material jetting (MJ) with six articles (22%), fused filament fabrication (FFF) and selective laser melting (SLM) with four articles each (15%), binder jetting (BJ) with one article (4%), and three articles (11%) which used a resin or polymer process that was not specifically described (although visually appeared to be either MJ or stereolithography). Considering the International ASTM 52900 standards classifying AM technologies,[1] SLS and SLM fall under the Powder Bed Fusion category, meaning that thirteen articles (50%) of articles used this technology.

Table 3. Summary of software and 3D printers used in articles.

Reference	CAD Software	3D Printer	Type	Material	Other Technology
[33] 2013 Journal	-	Objet Eden 350V	MJ	FullCure 720 (model material) and FullCure 705 (support material)	ANSYS CFX for computational fluid dynamics
[34] 2014 Conference	-	Objet Eden 350V	MJ	FullCure 720 (model material) and FullCure 705 (support material)	ANSYS CFX for computational fluid dynamics
[35] 2015 Journal	-	-	-	Undisclosed polymer	MATLAB for flight path calculations
[46] 2016 Journal	Geomagic Design	Zcorp z650	BJ	zp150 (plaster) powder	Artec MHT 3D scanner
[48] 2015 Conference	-	-	-	-	-
[49] 2015 Conference	-	-	SLM	Titanium (Ti–6Al–4V)	-
[50] 2014 Journal	Altair SolidThinking Inspire	Renishaw AM250	SLM	Titanium alloy	-
[51] 2016 Journal	Geomagic, Solidworks	SLM Solutions SLM125	SLM	Titanium	Autodesk Mechanical Simulation, Creaform EXAscan 3D scanner
[52] 2018 Journal	Genesis Design Studio 14.0, Solidworks, Magics 19.0	EOS M280	SLM	Titanium Ti64	HyperMesh 13.0, CT scanner
[19] 2019 Journal	Solidworks	Undisclosed, Wanhao Duplicator i3	SLS, FFF	Polyamide (nylon), ABS	3D scanner
[53] 2019 Journal	CREO 3.0, Rhinoceros 5.0	Objet Connex 3 260	MJ	FullCure 720 (rigid parts), FullCure 930 (lattice structure), FullCure 705 (support material)	3D Systems Sense 3D scanner
[47] 2016 Conference	CATIA	-	-	Resin	-
[54] 2018 Journal	Geomagic Studio	MakerBot Replicator 2	FFF	NinjaFlex (TPU), PLA	3D Systems Sense 3D scanner
[55] 2018 Conference	MATLAB, JIGSAW mesh generator	Stratasys Objet500 Connex3	MJ	VeroWhite (resin)	-
[56] 2017 Journal	-	-	MJ	Stratasys photopolymer MED610	MATLAB for data analysis
[36] 2010 Book Chapter	Geomagic Studio	-	SLS	DuraForm Polyamide (nylon)	RealScan USB 200 3D Scanner
[42] 2010 Conference	-	-	SLS	Polyamide 12 (nylon)	-
[40] 2011 Journal	Geomagic Studio	-	SLS	DuraForm Polyamide (nylon)	RealScan USB 200 3D Scanner
[41] 2011 Journal	-	-	SLS	Polyamide 12 (nylon)	-
[43] 2011 Journal	Solidworks	EOS P390	SLS	Polyamide 12 (nylon)	-

[37] 2012 Journal	Magics	-	SLS	DuraForm Polyamide (nylon)	eScan 200 3D scanner
[38] 2013 Journal	Magics	-	SLS	DuraForm Polyamide (nylon)	eScan 200 3D scanner
[39] 2013 Journal	Geomagic Studio	-	SLS	DuraForm Polyamide (nylon)	RealScan USB 200 3D Scanner
[44] 2016 Conference	-	-	-	Undisclosed polymer	-
[45] 2018 Journal	Meshmixer, Gensole, Solidworks	Cubicon 3DP-110F	FFF	-	EinScan Pro 3D scanner
[57] 2017 Journal	Solidworks	Objet Connex 350. Markforged Mark Two, Dimension uPrintPlus, Fortus 900	MJ FFF	ULTEM resin ABS, carbon fiber composite	-

Abbreviations: BJ = binder jetting, FFF = fused filament fabrication, MJ = material jetting, SLM = selective laser melting, SLS = selective laser sintering

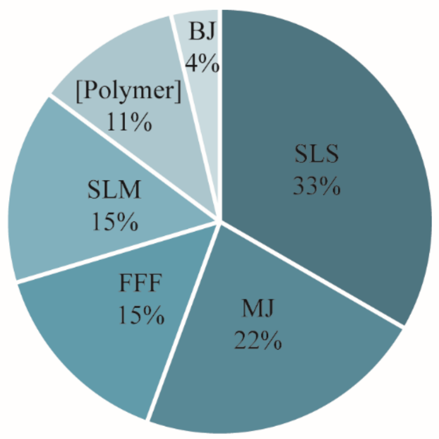

Figure 6. AM technologies used to manufacture products.

All SLM studies utilized titanium, and all SLS studies utilized polyamide (nylon) materials. FullCure 720 was the next most popular material used in three articles (12%) on Stratasys Objet machines, followed by Acrylonitrile Butadiene Styrene (ABS) in two articles (8%) and all other materials in Table 3 only appeared once. Four of the articles (16%) did not specify the material used.

A broad range of CAD software has been used to design and optimize products within the studies, with the most popular being Solidworks and Geomagic (various versions) which were each used in six articles (23%), followed by Magics (n=3, 12%), and several other software packages which may be common for design engineers (e.g. Rhinoceros and CREO), or specific to certain industries (e.g. Gensole). Nine articles (35%) did not provide any indication of what software was used to design or optimize products. This oversight presents difficulties for follow-up investigations by external researchers, and journal editors and reviewers should be encouraged to require complete methodologies in future.

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An important finding from this review was the use of 3D scanning within articles to complement the design and optimization of sporting products. Eleven articles (42%) used a 3D scanner to capture personalized human geometry such as legs for baseball[46] and football (soccer) leg guards,[53] or feet for personalized insoles.[36-40, 45] This shows a strong relationship between these digital technologies.

Opportunities and limitations identified within each study were also collected, and the recurring findings are listed below:

- Opportunities:
    - Combined with 3D scanning, AM provides new cost-effective means for producing athlete-specific products[36, 39, 40, 46, 53, 54]
    - Parametric CAD files allow for almost limitless iterations of a design to suit specific users and conditions[19, 41, 42, 50, 51, 56, 57]
    - Part consolidation to reduce assembly costs and open new possibilities with multi-material AM[51, 53, 54]
    - Complex geometries that would not be manufacturable using subtractive methods provide new opportunities to improve performance[42, 44, 55]

- Challenges:
    - Long-term durability of AM materials for sports applications is unclear, with most studies not containing longitudinal analyses, and featuring limited sample sizes[33, 35, 42, 53]
    - AM is typically a slower process than traditional manufacturing processes[51, 54]
    - Postprocessing can be time- and labor-intensive[52, 54]
    - Many parts produced with AM must still interface with a conventional part to form a product, limiting geometry[49, 51]
    - Optimization software still requires manual intervention and an understanding of design for AM[52, 55]
    - New products produced through AM may not meet sporting regulations[19, 44]
    - Laboratory testing may not translate to real-world conditions[19, 34, 56]

Discussion

Across all literature included in this review it was clear that authors held an optimistic opinion of AM as it relates to sporting applications, despite results that may have been on par with, or performing worse than, conventional products. Collectively, AM was used in attempts to develop products that improved safety and comfort,[36, 39, 46, 49] improved performance,[19, 41, 50-52] or utilized an alternative production method and material to achieve the same outcome.[33-35] However, there was no evidence of scientific studies supporting the development of mainstream products for companies like Adidas, and no evidence of the bespoke products developed in the literature leading to new commercial products. Academic and commercial developments of additively manufactured sporting products appear to be occurring separately, and collaborations between academia and industry are likely to be protected by intellectual property (IP) non-disclosure agreements. IP is a complex issue for AM, particularly due to the digital nature of the technology that makes copying, sharing and modifying files relatively easy.[58] It is further complicated by the opportunity for personalized products, as with many of the products identified through this review, especially when those designs are based off someone's own body data. This is an area of interest for future research.

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The more mature medical AM field provides a useful contextual comparison in order to address the research question of this study, with the opportunities for personalized products to improve health and recovery sharing much in common with sports, and opportunities to utilize other digital technologies like 3D scanning, as well as computed tomography (CT) or magnetic resonance imaging (MRI), well documented.[59] A 2016 study by Tack et al.[60] investigated the use of AM in surgical cases, where studies had featured three or more cases or clinical trials, finding 227 papers for review. A similar 2016 study which excluded articles related to bioprinting, dentistry and limb prosthetics analyzed 158 studies,[61] while another specific to plastic and reconstructive surgery analyzed 103 articles.[62] A more focused systematic review of AM for patient-specific surgical guides reviewed 38 publications,[59] while another on patient-specific immobilization devices used in radiotherapy treatments found 18.[63] Compared to these reviews of medical applications, where the average number of papers reviewed was 131, this broad systematic review of AM for sports applications with only 26 publications is significantly smaller than medical applications and reinforces comments by Mawale et al.[9] that research into sports applications is only at the "initiating phase" compared to the more established medical industry.

A finding that is common between this review and others conducted within medical systematic reviews is the growth in AM research around the year 2010. Tack et al.[60] identified 30 relevant publications between 2006-2010, compared with the period 2011-2015 which found 189. Popescu et al.[59] also noted an increase in literature following the 2009 expiry of key Fused Deposition Modeling (FDM) patents, although the authors acknowledge there was no specific evidence to support this correlation. Data from Martelli et al.[61] showed a slightly earlier growth in research starting in 2007, with the previous two years only revealing 3 studies per year, compared to 16 published in 2007, an annual number that has been maintained, or slightly increased, since this time. Therefore, while the number of articles published on sporting applications is significantly lower than medical applications, the recent growth around the year 2010 supports evidence that improving technologies, materials and access to AM is driving research across industries.[5, 64]

Further evidence of sports applications being a relatively new area of academic research is in the spread of literature; other than cycling and running/walking, all sports meeting inclusion criteria have been featured in a single study, or in the case of Badminton, several studies by the same author group. As a result, research findings have not been validated by multiple research groups, and concepts have not been developed by many different researchers to build a body of evidence supporting the use of AM for a particular application. The extent of testing within the literature also suggests the development of sports products for AM are preliminary concepts, with several studies resulting in critical failure of parts,[42, 43, 52, 53, 57] while some studies featured a single sample for testing (although may have included several iterations for simulated tests).[34, 35, 51] In order to reach the level of acceptance and innovation experienced within the medical industry, consistent and ongoing research is required by sporting product designers within academia and industry, and value must be placed on funding research that may improve the safety, comfort and performance of athletes at all levels of competition and recreation. This includes clearer reporting in literature of the hypothesis or goals for AM products, and whether achieving a comparable performance attribute to a standard product is desirable.

To support this growth, research must aim to better report methods and technologies within publications. As described previously, 11% of articles did not report the type of print technology employed to produce parts and 16% of articles did not report the material used. Furthermore, as shown in Table 3, 36% (n=9) of articles did not describe any software used to design or optimize products and 52% (n=13) of articles did not name the 3D printer used. Such reporting is critical to the reproducibility of research and has been discussed as a current issue by Gao et al.,[64] alongside issues of variations between AM technologies, limiting the ability for researchers to build new experiments to either validate or progress published material.

It is important to note that while rigorous in methodology, this review did not search through a large number of databases, and as a result, it is possible that some relevant literature was not uncovered. It is also possible that the search phrases, which included both general sports keywords as well as specific ones, missed some studies that may have been extremely specific in their research focus, or published in conference proceedings not indexed within major academic databases. However, it is unlikely that any missing articles would significantly alter the findings and recommendations of this research, and the methodology employed will allow future follow-up studies to accurately measure changes over time.

Conclusion

As a result of this study it is possible to conclude that additive manufacturing has yet to become a hit within academia for sporting applications. Despite exemplars frequenting 3D printing and additive manufacturing news websites, manufacturing trade shows and conferences, little scientific evidence exists to support the adoption of AM to produce sports products, with only twenty-six peer reviewed articles identified up until May 2019. Overall, twelve different sports were identified as having been the focus of new additively manufactured products with only badminton, cycling and running/walking being featured in more than a single article. This indicates a broad interest in applications of AM in sport, but with potentially limited opportunities or funding for follow-up investigations. The results also indicate the relatively recent emergence of sports as a research focus, with empirical evidence published beginning in 2010 despite earlier discussions within broader AM literature about the good alignment of AM opportunities with sporting applications. Through objective collation of the evidence to-date, this research cuts through the hype surrounding the use of AM to manufacture sporting products and highlights the need for rigorous, sustained and ongoing research in order to support manufacturers, product designers and athletes of all experience levels.

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Supplementary Data

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