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Competitive and technology intelligence to reveal the most influential authors and inter-institutional collaborations on additive manufacturing for hand orthoses

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ABSTRACT Additive manufacturing (AM) is revolutionizing the health industry, where it provides innovative solutions for the production of personalized devices, such as hand orthoses. However, the scientific research dynamics in this topic have not yet been investigated. This study aims to fill this gap through the application of a competitive and technology intelligence (CTI) methodology enhanced by a scientometric and network map analysis. Major advances in the fabrication of hand orthoses using AM, the presence of collaborations, and the most influential authors were determined. Specifically, network map analysis, bibliographic occurrence and bibliographic coupling were conducted on documents retrieved from Scopus and the Web of Science (WoS), and on patents from more than 104 authorities. Results showed only nine published patent families and 34 research articles on this topic from 2006 to 2016. Ten papers concern static orthoses, while 24 deal with dynamic orthoses and exoskeletons. The indegree and outdegree parameters and the betweenness centrality of these documents enabled us to determine the most cited authors and instances of collaboration (papers co-authored between institutions). Dr. Paterson A. M. J. was the most influential author, with four publications with the highest betweenness centrality in the network (189), which accounted for the most cited document with five citations. The institution with the most publications was Loughborough University, with four papers, and the collaboration between affiliations was rare. These documents review important aspects of manufacturing orthoses using AM, and additionally pay particular attention to the importance of personalised orthoses where AM contributes. Notably, these papers focused primarily on studies for the development of a methodology for the fabrication of hand orthoses using AM, but they do not present any application. This research provides insights to better understand the dynamics of research and development in the orthopaedics domain, specifically for hand orthoses.

KEYWORDS 3D printing, additive manufacturing, betweenness centrality, bibliographic coupling, competitive intelligence, hand orthoses, network map analysis, scientometrics

1. INTRODUCTION

The competitive and technology intelligence (CTI) methodology is a process where information is systematically and ethically gathered to be analysed and further transformed into valuable results that can strengthen decisions for innovation and product development (Rodríguez-Salvador and

Tello-Bañuelos 2012). Public documents, such as patents or scientific publications, represent useful sources of information for CTI purposes.

While patents register technological inventions (Archibugi and Pianta 1996), scientific documents aim to publish original research advances. Both represent valuable resources to identify and monitor the progress of science and technology (S&T) including predominant research areas, emerging technologies, top researchers, most active institutions in the field and collaborations. They also support decision-making processes for research and innovation efforts (Archibugi and Pianta 1996; Bonino et al. 2010; Fabry et al. 2006; Rodríguez-Salvador et al. 2014).

When analysing such documents, applying scientometric methods with CTI can provide a better assessment of S&T production (Bornmann and Leydesdorff 2014; Mingers and Leydesdorff 2015). These methods use complex tools to process information from dozens to thousands of patents or scientific publications, not only from well-established research areas, but also for emerging technologies such as AM (Bakhtin and Saritas 2016; Leydesdorff et al. 2015; Leydesdorff and Milojević 2015; Oldham et al. 2012; Porter and Youtie 2009; Rotolo et al. 2015).

Although new developments have less information available than established technologies, using scientometric tools is required to significantly dispel the uncertainty surrounding emerging technologies. Tools like bibliographic occurrence and bibliographic coupling can be applied to determine the impact, growth or evolution of science (Biscaro and Giupponi 2014; McCain 1990; White and Griffith 1981; Zhao and Strotmann 2008). While bibliographic occurrence evaluates the presence of specific references contained in scientific documents, bibliographic coupling refers to the frequency of references shared between two or more scientific documents. The higher the bibliographic coupling, the higher the impact of the cited documents (Biscaro and Giupponi 2014). Of the two tools, bibliographic coupling is more suitable for the identification of fundamental research domains (Kuusi and Meyer 2007; Small 1973; Zhao and Strotmann 2008). Additionally, the authors with more influence in a certain area of research can be determined using indegree and outdegree parameters or centrality measures, which are commonly applied in network map analysis. The indegree parameter counts the times that each analysed document is cited by other publications, and the outdegree counts the publications cited in the analysed documents. Furthermore, the betweenness centrality measurement has high value for network map purposes. It enables grading of nodes according to their positions. A grade is applied based on the shortest number of paths that pass through a particular node. If a node is in a position that connects different aggregates of nodes, this node will have a higher betweenness centrality (Brandes 2001). This measure was used in this research to determine the most influential author by noting if an author is connected to more authors, not only to documents in reference lists. Institutional collaboration can be clearly visualised and analysed through network map analysis, which shows the interaction between them.

Recently, Rodríguez-Salvador et al. (2017) applied scientometric tools on scientific and patent literature from 2000 to mid-2016 to uncover the knowledge landscape of 3D bioprinting. We also presented a first approach to study the incursion of AM on hand orthoses at the 3rd International Conference on Progress in Additive Manufacturing (Pro-AM) held in Singapore in May 2018 (García-García and Rodríguez-Salvador 2018). This research determined that AM is already used in the production of hand ortheses. Materials, processes and methods for data acquisition were also detected. However, the current study focuses on the identification of the most influential authors and co-authoring institutions that have carried out research for the use of AM in hand orthoses.

Such orthoses are of significant relevance for treating hand disabilities related to broken bones, congenital conditions or cerebrovascular diseases (Colditz 1996; Colditz 2002; Coppard and Lohman 2015; Fess 2002; Imms et al. 2016). They are used as part of rehabilitation programs to support the affected limb by immobilising it. The most common orthoses are static, but there is also another type of orthosis: the dynamic orthosis. This type of orthosis provides the patient with a limited amount of movement through a mechanical assembly—such as rods, pins, and springs connected to the orthosis's main body—which is made using the same materials as conventional, static orthoses. Static orthoses are fabricated using diverse materials. Plaster of Paris is the most common, but thermoplastics is also widely used (Cassell et al. 2005; Colditz 2002; Coppard and Lohman 2015; Fess 2002; Fess 2005; Schultz-Johnson 2002; Schwartz and Janssen 2005).

Normally, orthoses can be manufactured in batches using standardised hand measurements (such as small, medium or large), but using personalised orthoses according to the patient's anatomy and type of treatment, allow for better patient recovery (Fess and McCollum 1998; Kim and Jeong 2015; Paterson et al. 2015). AM is a technology that can be used for the fabrication of personalised orthoses.

AM, also known as 3D printing, rapid prototyping or free-form fabrication (FFF) (Espalin et al. 2010; Ventola 2014), is a novel manufacturing process used for fabricating objects by depositing materials in layers from digital models. The models can be generated either through computer aided design (CAD) software or image acquisition methods, such as computerised tomography (CT) scans, magnetic resonance imaging (MRI) or 3D scanning. AM has many advantages over traditional manufacturing, such as reducing material waste, minimising manufacturing cost for complex parts and manufacturing unconventional, personalised shapes (Banks 2013; Basiliere and Shanler 2015; Davey et al. 2011; Espalin et al. 2010; Paterson et al. 2010; Schubert et al. 2014; Ventola 2014). This increases the attractiveness of AM technology. It is a very versatile technology that has the potential to fabricate personalised medical devices, such as prostheses or orthoses.

2. METHODOLOGY

The scientometric tools of bibliographic occurrence and bibliographic coupling, as well as network map analysis, were used within the competitive and technology intelligence (CTI) methodology of Rodríguez-Salvador et al. (2017), with the aim of determining the most active and most influential author and understanding the level of collaboration (co-authoring) between institutions working on the fabrication of hand orthoses using AM.

The process began with the determination of the most suitable keywords with which to build a search query for both scientific and patent databases. This stage included a review of publications on rehabilitation, therapy and orthopaedics (García-García et al. 2018). The terms obtained were then assessed by experts on hand therapy who asked to remain anonymous. Four main keyword categories were determined as follows: anatomy (e.g., hand, finger, phalangeal), technology (e.g., 3D printing, AM), application (e.g. rehabilitation for stroke) and medical devices (e.g. orthosis, splint). Figure 1 shows a Venn diagram of the keyword groups. These keywords were used to build a general search query in which Boolean operators, proximity terms, truncators and wild cards were applied. A set of 100 searches was performed before arriving at a final search query approach. The general query used was based on the following:

TITLE-ABSTRACT-KEYWORD(((("3D print*") OR ("rapid prototyp*") OR ("additive manufact*") OR ("solid free form fabric*") OR ("fuse deposit* model*") OR ("selective Laser sinter*") OR (stereolithography) OR (photopolymeri?ation) OR "reverse engineering") AND ((hand OR wrist OR finger OR "upper limb") W/5 ("static progressive splint*" OR "serial static splint*" OR "casting motion to mobile stiffness" OR orthos?s OR orthotic* OR orthop?edic OR splint* OR brace* OR cast* OR rehabili* OR aid OR paresis OR "post-stroke")) OR ((dynamic W/10 orthos?s) AND ("prototype")) OR (dynamic W/10 splint*) OR (exoskeleton))

Where W/# indicates a search within a specified number of words. This general query was then modified according to each of the databases consulted.

Patseer, an online patent platform that covers more than 104 leading patent authorities, was used to collect and analyse patents (Sinha and Pandurangi 2016). To

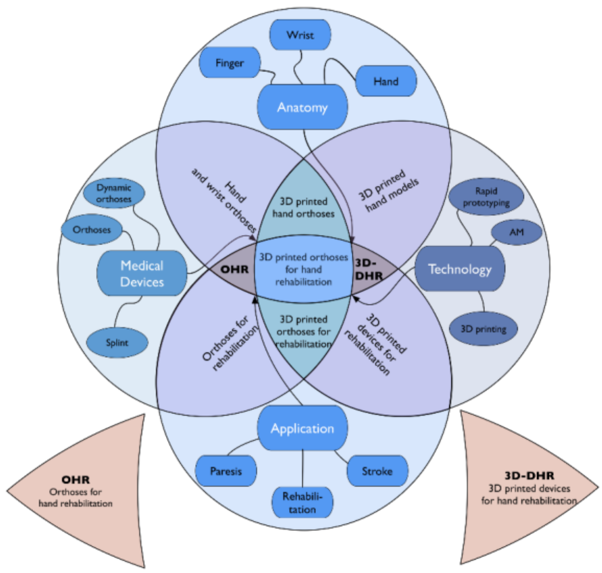

Figure 1 Main terminology categories. Keywords grouped by anatomy, technology, applications and medical devices.

search for scientific documents, Scopus and the WoS were utilized (García-García et al. 2018).

Scopus, at the time of the search, contained information from more than 20,000 journals (Elsevier 2016), while the WoS covered information from more than 13,000 journals (Thomson Reuters 2011). The time frame to be searched was defined as 1980 to 2016 (2016 was the year in which the information gathering for this study concluded). The year 1980 was chosen because the first reported works on 3D printing technology were published in the 1980s (Dormehl 2018).

The next step in the methodology was the cleaning process, in which those publications not related to the topic of interest were discarded. During this step, publication titles and the names of authors and institutions were homogenised and the data deduplicated, eliminating repeated items from the data set.

Then, a bibliographic network map of the publications was generated to identify the most cited authors on the subject. This was achieved through bibliographic coupling, determining the betweenness centrality and finding the indegree and outdegree parameters. A collaboration analysis was also carried out using network mapping to find partnerships between the main affiliations advancing the fabrication of hand orthoses using AM.

3. RESULTS

The overall number of publications obtained from the searches of the three databases (Scopus, WoS and Patseer) was lower than expected. Only 15 published patent families were identified in Patseer, while a total of 46 publications were obtained from Scopus and 33 from the WoS. A further cleaning process homogenised the titles of patents and articles, the names of the authors and inventors and the titles of affiliations or institutions. The cleaning process also eliminated duplicates and those patents and articles that, despite containing the terms of the query, were not related to the topic. After this process, a total of 9 published patent families were obtained from Patseer and 34 research articles were obtained from Scopus and the WoS. Figure 2 shows the number of publications per year, from 2006 to 2016 (1980 was considered initially, however no information was detected), for each database.

The patent families are listed in reverse chronological order in Table 1. Seven patents were published between 2014 and 2016, one patent in 2010, and the remaining one in 2007.

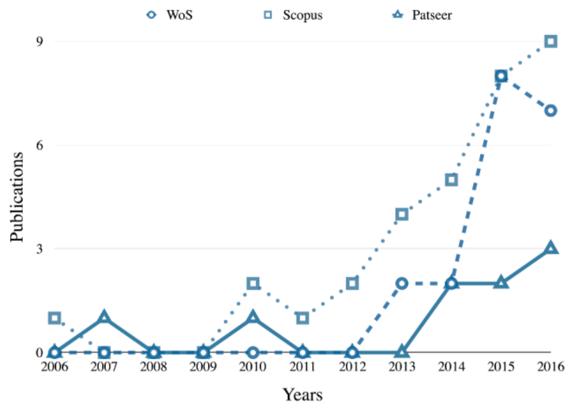

Figure 2 Publications and patents per year for the WoS, Scopus, and Patseer.

The analysis also showed that the United States has five patents published, making it the most prolific country in the field. From the patents retrieved, only two were closely related to orthoses: 'Methods for integrating sensors and effectors in custom three-dimensional orthosis' from Turkey and 'Systems and methods for generating orthotic device models by surface mapping and extrusion' from the United States. Only one author published more than one patent: James Schroeder, whose patents were published in 2007 and 2010 and are related to the customization of implants, prostheses, and surgical instruments and methods of manufacture.

Of the 34 research articles from Scopus and the WoS, 24 were about developing dynamic orthoses or exoskeletons for rehabilitation, and only ten were related to static orthoses. As a preliminary result, it was observed that the article with the most citations was A. M. J. Paterson's, published in 2010 (Paterson et al. 2010): 'A review of existing anatomical data capture methods to support the mass customisation of wrist splints.' A further bibliographic network map (Figure 3) was generated to visualize the connection between the publications and their references, and to carry out bibliographic coupling. The map was plotted in Gephi™, using the Force Atlas Algorithm. This algorithm is commonly used to emphasise complementarities and to spatialise networks with a small amount of data (Bastian et al. 2009; Jacomy et al. 2014). Figure 3 shows the network map of the documents and their references, where the size of the nodes is proportional to the indegree parameter, which displays the number of citations each document has (Gmür 2003) and thus identifies highly cited publications. On the other hand, the outdegree parameter is proportional to the number of references contained in each document.

Table 1 Patent families gathered from the patent search in Patseer.

Patent No (Pub. Date)	Title	Assignee	Inventor	Priority Country
BR102014029649A2 (31 May 2016)	Manufacturing process articulated prostheses from a combination of rigid and flexible material in one piece (Gomes da Fonsêca et al. 2016.)	Fundaçao Universidade de Brasilía	Gabriela Freitas Gomes da Fonsêca,Jeferson Andris Lima Lopes, Jorge Ribeiro Cunha da Silva, Lucas Coelho de Almeida, Marcelino Monteiro De Andrade	Brazil
WO2016071773A2 (12 May 2016)	Methods for integrating sensors and effectors in custom three-dimensional orthosis (Karasahin 2016)	Deniz Karasahin	Deniz Karasahin	Turkey
US2016101571A1 (14 Apr 2016)	Systems and methods for generating orthotic device models by surface mapping and extrusion (Schouwenburg et al. 2016)	Sols Systems Inc.	Kegan L. Schouwenburg, Daniel Bersak, Jeff Smith, Ciaran N. Murphy	United States
US2015328840A1 (19 Nov 2015)	Use of additive manufacturing processes in the manufacture of custom wearable and/or implantable medical devices (Zachariasen and Cropper 2015)	Joseph T. Zachariasen Dean E. Cropper	Joseph T. Zachariasen, Dean E. Cropper	United States
WO2015095459A1 (25 June 2015)	Robotic finger exoskeleton (Deshpande and Agarwal 2015)	Board of Regents, The U. of Texas System	Ashish Deshpande, Priyanshu Agarwal	United States
JP2014533975A (18 Dec 2014)	Customisable embedded sensors (Ranky and Mavroidis 2014)	Northeastern University Richard Ranky Constantinos Mavroidis	Richard Ranky, Constantinos Mavroidis	Japan
CN203935304U (12 Nov 2014)	Novel bionic exoskeleton artificial limb controlled by cable wires (Xiogjiao et al. 2014)	Xing Xiongjiao Yuan Ning Zheng Haolin	Xing Xiongjiao, Yuan Ning, Zheng Haolin	China
WO2010120990A1 (21 Oct 2010)	Personalized fit and functional designed medical prostheses and surgical instruments and methods for making (Schroeder 2010)	James Schroeder	James Schroeder	United States
WO2007045000A2 (19 Apr 2007)	Personal fit medical implants and orthopaedic surgical instruments and methods for making (Goodman et al. 2007)	Steven L. Goodman, Kyujung Kim James Schroeder Vantus Technology Corp.	Steven L. Goodman, Kyujung, James Schroeder, Vantus Technology Corp.	United States

These categories have the highest frequency of occurrence. Patents, letters, notes and standards were also cited in the documents obtained, but so infrequently that they are barely visible on the map.

The higher numbers of nodes are for publications related to dynamic hand orthoses, as seen in Figure 3. However, the analysis showed that bibliographic information related to AM of dynamic hand orthoses came mostly from conference papers (80 percent), and the majority did not have citations up to 31 December 2016. The documents related to static orthoses were mostly journal articles,

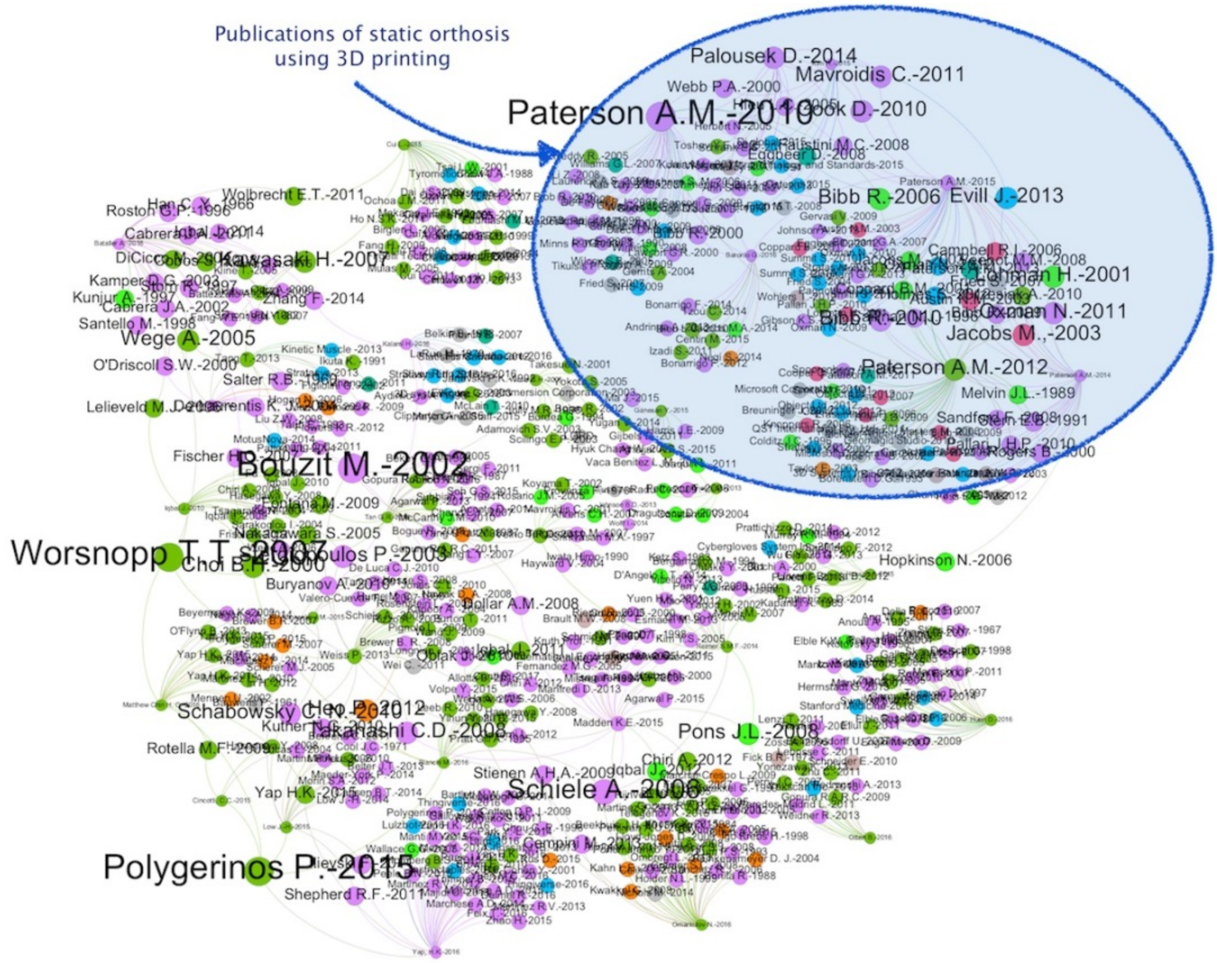

Figure 3 Bibliographic network map based on the indegree parameter and kind of document. The colours indicate document type. Magenta = papers, dark green = conference papers, blue = websites, grey = manuals, orange = reviews, light green = books, turquoise = theses. The size of the nodes are proportional to their indegree parameters.

and only ten percent were conference papers. These documents and their references are circled in Figure 3.

The lack of interaction between publications related to dynamic orthoses and those for static orthoses can also be seen in Figure 3. Only one such connection can be noted: 'Hopkinson (2006)' (Hopkinson et al. 2005), which is shown in light green, on the far-right side in the middle of the map. This single connection was cited by Paterson et al. (2014) from the set of static orthoses and by Madden and Deshpande (2015) from dynamic orthoses.

The most cited author from the analysed documents was Paterson, who published four pieces across a six-year period: Paterson et al. (2010), Paterson et al. 2012), Paterson et al. (2014) and Paterson et al. (2015). These publications discussed methods for image capturing and fabricating orthoses using 3D printing.

Additionally, the betweenness centrality was estimated to identify the authors with more influence on the topic. This parameter is often used to grade nodes on network maps according to their spatial position, based on the number of shortest paths between two nodes that pass through a particular node (Brandes 2001). For instance, a node has a high betweenness centrality if it connects different parts of the network to each other, like a train station—different trains from different places running through one centralized station. From the information retrieved, only eight nodes had a betweenness centrality value (Table 2), while the value for the other nodes was zero. These eight nodes have an actual betweenness centrality value because they connect, not only to nodes of references, but also to some of the different publications retrieved. It should be noticed that Paterson is displayed three times in this list—with values of 189.0, 130.0 and 34.5—which shows the notable influence of the author on the flow of the knowledge network.

Table 2 Weighted indegree, weighted outdegree, and betweenness centrality of the eight nodes with a betweenness centrality value. Times cited = times cited in retrieved documents only.

Publication Label	Weighted Indegree	Weighted Outdegree	Times Cited	Betweenness Centrality
Paterson (2010) (Paterson et al. 2010)	5.0	33.0	5	189.0
Paterson (2012) (Paterson et al. 2012)	3.0	41.0	3	130.0
Madden (2015) (Madden and Deshpande 2015)	1.0	27.0	1	44.0
Weiss (2013) (Weiss et al. 2013)	1.0	23.0	1	41.0
Palousek (2014) (Palousek et al. 2014)	3.0	15.0	3	34.5
Paterson (2015) (Paterson et al. 2015)	1.0	44.0	1	34.5
Velho (2011) (Velho and Zavaglia 2011)	1.0	11.0	1	11.0
Tang (2013) (Tang et al. 2013)	1.0	12.0	1	8.0

Figure 4 shows the map of the bibliographic coupling carried out among the publications about static hand orthoses, while Figure 5 shows the map of bibliographic coupling for dynamic hand orthoses. In both figures, the size and colour of the nodes are proportional to their indegree parameters; the higher the value, the bigger and darker the node. Similarly, the citations received by each node are represented by incoming arrows, while the outgoing arrows are connected to the citing documents.

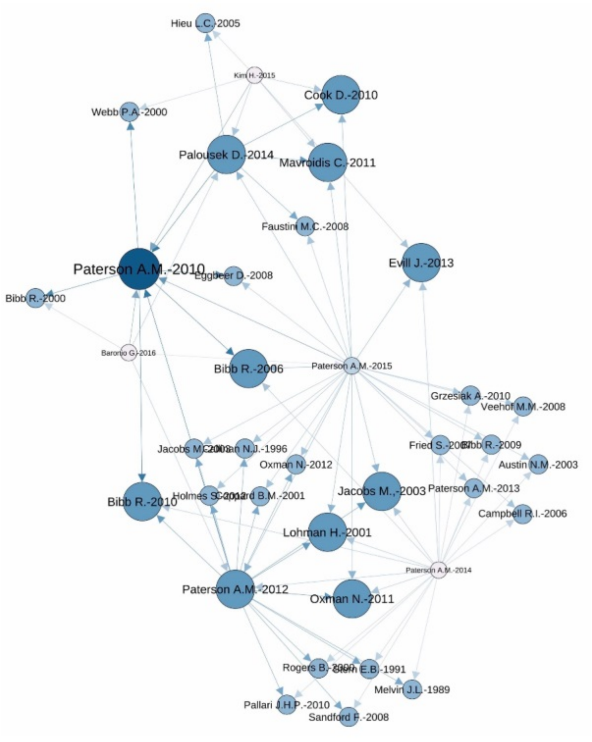

Figure 4 Bibliographic coupling for publications in static orthoses for the hand.

The bibliographic coupling analysis observed that the highest number of coupled cites was 12, between Paterson et al. (2014), shown on the right side of the map in Figure 4, and Paterson et al., (2015), located in the map's upper corner. However, though the number of shared references was high, these sources were selected by the same author and were, thus, negated for our research purposes. The second set of documents coupled were Paterson et al. (2015) and Palousek et al. (2014), with four citations in common (namely, Faustini et al. (2008), Cook et al. (2010), Mavroidis et al. (2011) and Paterson et al. (2010)), as in Figure 4. Both Paterson (2015) and Palousek (2014) described methods for designing customised splints using 3D printing, while the cited papers from Faustini (2008), Cook (2010), and Mavroidis (2011) dealt with the use of AM for foot orthoses, serving as referents for

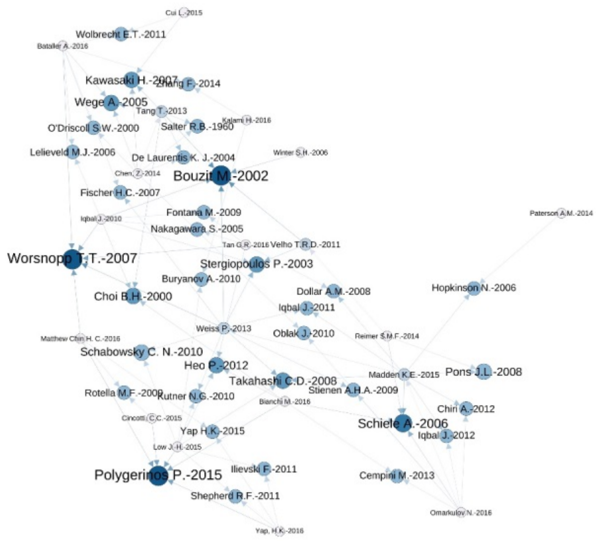

Figure 5 Bibliographic coupling for publications in dynamic orthoses for the hand.

researching methods applicable to personalised hand orthoses. For dynamic orthoses, there was a reduced number of papers coupled with their references. This was because there were no documents sharing more than two resources. As this resulted in a bibliographic coupling of less impact, the most cited documents were listed instead.

Table 3 lists the documents with more citations (4-5). From the documents listed in Table 3, Paterson et al. (2010) was the only one from the set of static hand orthoses, and this document was published by the institution with the most articles on the subject, Loughborough University.

The number of institutions with most publications was found to be limited. Despite this, Loughborough University had the most publications (four papers), followed by the National University of Singapore and Shanghai Jiao Tong University, with two articles each.

4. DISCUSSION

This study applied the scientometric tools of bibliographic occurrence, bibliographic coupling and collaboration network analysis to identify the institutions working on the development of hand orthoses using AM. Results revealed that the implementation of AM for developing personalised hand orthoses is not present in a high number of publications and collaboration between different institutions to publish jointly is rare.

From the 34 scientific publications detected, a total of 42 affiliations were identified. A network map analysis was carried out using Gephi™, in which only the affiliations with documents cited at least once were considered. This resulted in 20 affiliations. The highest number of affiliations working collaboratively was three: Loughborough University co-authored with the University of Manchester (Paterson et al. 2015) and the Royal Derby Hospital (Paterson et al., 2014). This was considered an important collaboration, not only for the number of affiliations involved, but because one of them is a medical institution. A second collaboration with a medical affiliation was found in Australia, where Curtin University's School of Physiotherapy and Exercise Science partnered with the Mechanical Engineering Department. These, however, were the only multidisciplinary collaborations the analysis discovered.

The limitations of this study lie in the novelty of applying AM to medical devices. While the first searches did not produce results when using terms related to dynamic orthoses, this changed after adding exoskeleton terms. Exoskeletons provide enormous advantages as, in many cases, they include sensors and electronic systems to improve rehabilitation (Iqbal et al. 2010; Worsnopp et al. 2007).

For this research, a co-citation analysis could not be carried out because of the small number of citations of the documents retrieved. Further analyses might embrace a higher number of publications as the application of AM in the development of orthopaedic devices is growing quickly.

Table 3 Publications with four or more citations.

Reference (Number of citations)	**Title**	**Cited by:**
Paterson et al. 2010 (5)	A review of existing anatomical data capture methods to support the mass customisation of wrist splints	(Paterson et al. 2012), (Palousek et al. 2014), (Kim and Jeong 2015), (Paterson et al. 2015), (Baronio et al. 2016)
Polygerinos et al. 2014 (5)	Soft robotic glove for combined assistance and at-home rehabilitation	(Cincotti et al. 2015), (Low et al. 2015), (Chin et al. 2016), (Yap et al. 2016), (Bianchi and Buonamici 2016)
Worsnopp et al. 2007 (5)	An actuated finger exoskeleton for hand rehabilitation following stroke	(Iqbal et al. 2010), (Weiss et al. 2013), (Tan and Robson 2016), (Chin et al. 2016), (Bataller et al. 2016)
Bouzit et al. 2002 (4)	The Rutgers Master II: new design force-feedback glove	(Winter and Bouzit 2006), (Iqbal et al. 2010), (Velho and Zavaglia 2011), (Weiss et al. 2013), (Tang et al. 2013)
Schiele and Van Der Helm 2006 (4)	Kinematic design to improve ergonomics in human machine interaction	(Reimer et al. 2014), (Madden and Deshpande 2015), (Omarkulov et al. 2016), (Bianchi and Buonamici 2016)

5. CONCLUSION

The scientific documents and patents involved in the personalisation of hand orthoses using AM were tracked back to 2006 through an enhanced CTI analysis using scientometric and network map analysis tools. The main knowledge area involved in this technology was found to be engineering. This information was corroborated in the collaboration analysis, which also disclosed that there has been minor participation of medical affiliations.

The analysis uncovered that the relevance of the information retrieved depends highly on the search strategy, which was carried out through the building and testing of different queries that were later validated by experts. Despite the low number of publications and patents obtained, the tools used to perform the analysis were useful for identifying main authors, institutions, and collaboration networks. Bibliographic occurrence and bibliographic coupling also constituted a valuable resource to understand knowledge diffusion through citations and to determine the dynamic of the research in a specific field. Furthermore, network map analyses enabled identification of publishing collaborations among affiliations. The methodology presented in this paper can be implemented to obtain a more complete analysis of the institution's research dynamics, particularly of emerging technologies. The tools used in this research can be applied over a wide range of areas to better understand the interaction between authors and affiliations, and to identify those most influential in their fields.

The proposed method would require future improvement by comparing results with opinions of experts to validate the main outcomes.

6. ACKNOWLEDGEMENTS

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7. CONFLICT OF INTEREST

The authors declare that they do not have any conflicts of interest.

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