Critical Assessment of Technological Development: What Can Bibliometrics Reveal?

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Scientific discoveries and innovations have served as the backbone for technological advancements, which can impart societal benefits and address critical needs in areas such as public health. For example, the modern hip implant has proven to be an effective treatment for joint-related diseases like arthritis. In the procedure, artificial joints are used to replace damaged or worn joints which can restore mobility and relieve concomitant pains. Today, many materials and implant parameters such as geometry, shape, and angle are available to surgeons, which can support a positive treatment outcome. Considering the significance, it is of interest to retroactively reflect on the technological evolutionary pathways.

Technological assessment is not new, but evaluating the process is necessary for optimizing best-case outcomes. Technological developments follow the cycle of need and solution, leading to both radical and incremental advancements.

In this work, we examine the research patterns and contributions that have shaped the technical discourse, using a commonplace hip implant material as an illustrative study from the scholarly perspective. In the span of 5 decades, output for polyethylene-related works grew from 2 in the late 1970s, to 2,123 publications in the 2010s, totaling over 4,600 publications with contributions from surgeons, biologists, engineers, physicists, and chemists. We disentangle components within the ecosystem and discuss the validity of insights from a bibliometric perspective. The reconciliation of technological developments to the impact is dependent on the aims of the assessment. Whilst it is found that bibliometrics analysis could help to disambiguate the technological innovations involving materials systems, advanced computer modeling, and detailed clinical trials, there are socioeconomic aspects, such as health systems, that are not easily validated. To maintain a greater degree of neutrality, the assessment of both public and private will benefit the interpretation of a multi-level system.

Keywords: biomaterials; hip implant; polyethylene; trend; wear; arthroplasty; technological assessment; bibliometrics; informetrics; research evaluation

Introduction

The generation of new knowledge and identification of emergent technologies is key to providing societal impact, gaining market competitiveness, and promoting growth. Technological advances do not arise singularly. They are borne out of a process with elements that lead to an expansive accumulation of knowledge. Technological assessment is not a new concept as a measurable means to capture the progress. The expectation of an assessment is to gain a better understanding of the knowledge process and evolution, which can optimize the pathway for arriving at best-case outcomes for technological developments. These insights affect various levels of beneficiaries such as direct end-users, and decision makers who direct policy or investments. The question we ask is, to what insights of the process do bibliometrics contribute? In this work, we examine the research patterns, contributions, and insights that have shaped the present knowledge base from a bibliometric perspective.

Central to our discussion is the technological development cycle, a system which can be skeletonized as three phases: (1) need, (2) solution, and (3) evaluation (Figure 1). Each phase has its own characteristics and routes. In the first phase, need represents an unfilled gap. Need itself is an impetus to observe and investigate origins of a given problem, forming fundamental research. This component contributes depth to the knowledge base, with which solutions are formed. In the second phase, the solution is the product of complex intermingling of elements such as societal need and population, economics, investment, and technical and infrastructural availability. The novelty of the solution can rank in various degrees, whether radical, incremental, or enabling (Riskin, Longaker, Gertner, & Krummel, 2006). Radical solutions
have the capability to shift leadership from the norm, whereas enabling solutions facilitate a subsequent related technology. When a secondary need arises, the cycle of generational developments begins for incremental solutions. In either of these cases, there may be the need for an enabling solution to gain the incremental or radical solution, which fundamentally shifts the approach. In a feedback loop, the chain of phases for every subsequent solution would lead to divergent discourse because of the co-evolution of each case over time (Coccia, 2012). We attempt to deconstruct the phases of this framework considering both direct (e.g. topical) and indirect (e.g. national or departmental contributors) parameters from the bibliometric record of academic research.

To illustrate possible insights from the research expansion, we investigate the case of polyethylene materials research for hip implant applications. Hip implants are an interesting case study because of the system dynamics, growth patterns, and socioeconomic relevance which contributed to the technological advancements seen today. There is a sufficiently long timeframe (1970s–2018) for longitudinal study with different stages of technological maturation. Comparing present research to early works, present day clusters and categories shifted from being clinical in nature towards a larger degree of involvement from science, technology, engineering and mathematics (STEM) disciplines in later years. This represents the value-add in bearing performance, to be detailed subsequently in this paper.

Background
Since Sir John Charnley pivotally introduced the low friction arthroplasty (LFA) in the 1960s, the orthopedic community gained more implant knowledge and experience that improved efforts for better device functionality and lifetime. The modern primary hip implant consists of a femoral head component and an acetabular component (Figure 3a). The acetabular component usually consists of a hard shell, and a soft (polyethylene) or hard (metal or ceramic) inner liner (socket) which articulates against the femoral head (ball). Each bearing combination exhibits material-dependent strengths and barriers (Figure 3b). For example, ceramic bearings are more susceptible to fracture. Historically, metal-on-polyethylene (MoP) bearings with a hard metal femoral component and a soft polyethylene acetabular liner has been widely used. While successful, one of the earliest problems associated with polyethylene-based articulations is wear. The repeated motions generated wear debris, prevalent in metal-on-polyethylene (MoP) articulations such as the Charnley LFA. Because debris accumulates around the implant, it often subsequently results in revision surgery.

Current statistics indicate the number of hip arthroplasty procedures worldwide are projected to continue rising in both developed and developing countries including the United States, Sweden (Nemes, Gordon, Rogmark, & Rolfson, 2014), New Zealand (Hooper, Lee, Rothwell, & Frampton, 2014), Germany (Pilz, Hanstein, & Skripitz, 2018), United Kingdom (Culliford et al., 2015), and Taiwan (Kumar et al., 2015). The demand for arthroplasty in the United States is expected to rise 174% between 2005 and 2030, to 572,000 procedures (Kurtz, Ong, Lau, Mowat, & Halpern, 2007). Growing incidences, longer life expectancy, increasing aging populations, and economic growth are factors which

![Figure 1: Flowchart depicting a data-driven assessment that explores the direct and indirect factors contributing to the cycle of technological developments.](image-url)
Figure 2: The knowledge expansion is a result of accumulated experiences, arising from the feedback loop in the technological development process. The early clusters represented by (a) research from 1990–1995 shows many keywords arose from the clinical setting. (b) The cumulative network map shows complementary and diverse clusters. The clusters were classified as follows: (1) manufacturing, processing; (2) tribology, surfaces; (3) biological properties; (4) couplings, alternative material systems; (5) clinical, surgical; (6) mechanical, design. Note that commonly occurring keywords such as ‘replacement’, ‘hip arthroplasty’ were omitted for clarity.

Figure 3: (a) Schematic of a modern hip implant. (b) Illustrations of issues pertaining to common hip implant materials.
What do bibliometrics reveal?

For our analysis, we look to common bibliometric tenets, activity measures, influence measures, and linkages in order to decouple these phases (Melkers, 1993; Narin, Olivastro, & Stevens, 1994) from their publication-related indicators. For each phase, the analysis focuses on obtaining empirical evidence (“who, what, when, where”) which are linked to their progression and origins (“how, why”). Table 1 lists the scenarios of indicators linked within the technological development process.

Being of a topical nature, the most direct interaction with contents of scientific knowledge occur at the keyword, title, and abstract levels of a publication. When mapped as co-occurrences, keyword or terminology linkage visualization is powerful for observing system dynamics over time. The expansion can be shown qualitatively in the networks, depicting both categorical expansion and cluster shifts. As with Figure 2, the network provides the bird’s eye view of research clusters and dynamics. However, the classification of the technological phase (need, solution, and evaluation) is more nuanced. Temporal deconstruction reveals a clearer picture of the evolution, where earlier years are dedicated to clinical observation of a need. Those keywords with early centrality become more prominent in terms of occurrence (node size) and link strength, affirming growth. The challenge in ascertaining technological topics bibliometrically is the level of granularity within a concept. This arises due to the fundamental limitation of the keyword itself from syntactic ambiguities, and from generational keyword or conceptual overlap in the network. Consequently, contextualization through supporting influential works or expert review, although laborious, creates a complementary frame of reference for identifying the phases of the technological life cycle. In short, a balancing measure which captures latent ideas within the text. Conceptual keywords may only be established near or around the end-stage, if at all. As with the Manufacturing Cluster example in Figure 4a, concepts like first-generation and second-generation highly crosslinked polyethylene were not represented in the network. Instead, they could only be associated with salient material characteristics, such as as “crosslinking” (solution_<sub>crosslinking</sub> and “oxidation” (evaluation_<sub>crosslinking</sub> secondary need_<sub>crosslinking</sub>) for the former, and “vitamin e” (solution_<sub>vitamin e</sub>). In this cycle, crosslinking represents an enabling technology which furthers growth of the field. Doping of the crosslinked material with vitamin E is an incremental solution to prevent oxidative degradation and improve user outcomes.

Where the topical levels address a finer granularity, inputs parameters such as category, department and journal parameters expand information insights. In particular, which communities did the need arise from? How and when did other communities begin to participate, and in what capacity? Could solutions have arrived earlier with a broader audience? Categorical inputs, which refer to the database-determined categories of a paper, are less direct to the topical approach but represent a skeletal and simplified form of the variations in research. In the case of hip implants, early publications are of a surgical nature, but the current knowledge domain represents both multidisciplinary and interdisciplinary topics.

Parallel developments and contributions from other fields, which may present as enabling technologies, such as computing (for finite element analysis, advanced signal processing techniques), or nanotechnology can be identified. Similarly, affiliation-based analysis is appropriate to profile entities involved. On a departmental level, the changes contribute to the demand. The loss of mobility can profoundly impact quality of life of an individual. By her early thirties, increasing pain and restricted range-of-motion made performing leg lifts and plies difficult for a career dancer. She left her dance company with worsening symptoms, but struggled with pain in demonstrations as a teacher until two hip arthroplasty procedures and rehabilitation provided relief (Buyls, Rietveld, Ourila, Emerton, & Bird, 2013). Besides physical impact, the loss of independence arising from age-related joint disease such as osteoarthritis (Palo et al., 2015), or from fracture pains sustained in accidental falls, can affect the social and emotional well-being of aging populations (Alexiou, Rougias, Evaritimidis, & Malizos, 2018). At present, the average lifetime of a hip implant is 15 years. For younger patients (<65 years of age), the likelihood of revision surgery is high especially those who lead active lifestyles (Christof Pabinger, Lothaller, Portner, & Geissler, 2018). The rising figures in orthopedic interventions presents as a public health issue and underscores the necessity of technological developments towards economically feasible hip implants which meet long-term performance demands of the user.

Table 1: Possible relations of publication parameters to the technological process.

| Publication parameter | Bibliometric insight to technology development cycle |
|-----------------------|-----------------------------------------------------|
| Text (e.g. keywords, abstract, title) | Technological topics and trends |
| Subject category | Disciplinarities (inter, multi, cross, etc) related to the development process |
| Departmental/institutional affiliation | Disciplinarities, origins of work |
| National affiliation | Interests of possible social or economic values |
| Journal | Audience, community |
within departmental participants and collaborations over time indicates the scholarly interest, partnership, origins. Despite their lower occurrence (Figure 4b), a larger proportion of highly cited papers occurred as collaborations between research institutes of a medical nature (e.g. orthopedic surgery, orthopedic biomechanics, pathology, and arthritis research departments) and of a technical nature (e.g. materials, biochemistry, mechanical engineering, bioengineering departments) on a national level.¹

The purpose of national profiling is in the understanding of participation numbers which signal community-specific needs or drivers on a national-level. The mechanism of research funding includes national policies and drivers, revealing interests of their society. For example, hip replacement rates vary between countries and were found to correlate with GDP and healthcare expenses (C. Pabinger & Geissler, 2014), and with the global need highlighted earlier. Medical devices like hip implants are often influenced by local ethnologic and social variations.

Ethnic population differences have been known to affect disease indications, age, and therefore the implant material to be used. Generally, non-medical technologies may be decidedly agnostic to demographic features but remain subject to other societal or economic components. As an example, the inputs of recent (2010s) participation of an emerging country such as China, could shift the discourse by addressing needs different to those of a leading country (United States). Asian scholars have noted the need for implant designs compatible with patient ethnicities (Huang, He, & Wang, 2012; Rawal, Ribeiro, Malhotra, & Bhatnagar, 2012) and different disease epidemiology compared to western studies (Lai, Wei, & Cheng, 2008; Yoon et al., 2014). This is in view of predominantly Caucasian-dominated demographics of western countries from which many implant designs originated. Critically, the contribution of emergent countries would present as latent features owing to the dominance of leaders. Therefore, for sufficiently mature environments

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¹ In single country publications, single institutional affiliations account for 43.3% of those publications, while multiple affiliations are 56.7%. Much like national collaboration, most international collaborations occur with the minimum number of affiliations. Collaborations face additional barriers related to a funding, institutional/infrastructural, administrative, or personal nature (Rendon et al., 2017), arguably more complex with less proximity. The establishment of consortia pairing leaders with emerging researchers could be one way to remove such barriers. We anticipate these arrangements would be especially beneficial for leading countries with low-to-middle income countries in situations without shared patient demographics.
Considerations in linking technological-clinical impacts

Bibliometrics provides the informetrics basis for origins of technology needs and solution phases. In the context of orthopedics research, assessments have addressed a specific aspect of publication output, corresponding to regions (Eom, Banne, Chowdhry, Chae, & Kim, 2015), countries (Çatal, Akman, Şükür, & Azboy, 2018; Cheng, 2012; Churchill et al., 2019), surgeons (Choudhari, Agrawal, & Shaikh, 2017; Saab et al., 2019), or publication impact (Ahmad et al., 2016; Li, Xu, Long, & Ho, 2019; Zhang et al., 2019). By contrast, in terms of technological advancements, comprehensive technical review papers are the norm (Merola & Affatato, 2019), focusing narrowly on innovations themselves. In technological assessment, it is insufficient to rely on bibliometric attributes alone. The conveyance of external factors surrounding its developments warrant further consideration for a complete analysis. Within the needs and solutions analysis, it would be more constructive to relay the direct output of research with respect to governmental funding on related topics to provide a multi-dimensional analysis.

For the third phase, the predecessor to a solution is observation. Likewise, a second observation is needed to evaluate its impact. Evaluation serves as the final link to the development cycle. Consequently, technological progress may be stagnated or tend towards enabling or incremental solutions in the interim. Therefore, considering the complexity of the entire system, a multi-level assessment approach is better suited to capture the systems-wide mechanism to the research developments.

Patents present as a shorter-term impact measure, where others may require time. On technology transfer, despite parallels in activity trends in patent and publications, evidence suggests that the technological impact of scholarly works is less direct. The answer lies in part from conflicting academic and industry cultures, evident when observing participants of either type of publishing. Scientific dissemination is mainly through academic journals and conferences. The peer review process necessitates full methodological disclosures in the public domain. Industry may participate in academic research, as seen earlier, but not all published in academic journals due to competitive interests. By contrast, patents are the preferred form of publication. In the latter, assignees are conferred limited exclusivity on a technology. As such, patents provide sufficient background information without complete disclosure to protect competitiveness. Therefore, the drivers of academic publication are not compatible with patent publication. Patents are also not necessarily reflective of active development work because intellectual property protection is in the interest of companies.

It is important to consider that the relationship between science and technology is not linear (Meyer, 2000), and does not follow sequentially from basic science to industrial development, although it is a convenient model. Conservative fields like the medicine are more reliant on past knowledge, and may require time in the order of years (such as clinical follow-ups). Therefore, mismatch between publications and usage rates, presumably the driver and impact respectively, may arise from disengagement of technology and impact (Figure F1). Publications address a broad range of issues, which may be mundane in terms of innovation. Some of the process between technology and evaluation cannot be simply measured because of complexity like industry involvement, governance, and regulatory compliance, particularly in applications involving in vivo human usage (Wienroth, McCormack, & Joyce, 2014). Translated technologies which undergo the processes are a limited subset of innovations, presumably with patents. As seen earlier, patent-cited works accounted for 1% of total publications, supporting the possibility of disengagement with technological publications. Compounding this, delays in time to outcome of a clinical setting would potentially increase the mismatch. In implants, a lower revision rate is preferred, but these do not present present until ~10–15 years after

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2 Patent application trends show that numbers related to polyethylene grew between 1970 and 2018, with the peak of applications in the 2000s. These trends are consistent with academic publishing. Unlike publishing records, patent trends have greater pre-1990 activity compared to publications.

3 Patent-cited publications (Scopus data, 1,517 records for topic cluster “Polyethylene; Volumetric Wear”) also indicate that about 1% of the publication records were cited in a patent between 2009 and 2018.

4 The largest contributors of academic publishing are universities and research institutes (e.g. University of Leeds, Anderson Orthopaedic Research Institute, Massachusetts General Hospital, and University of Iowa). Corporate (e.g. Exponent, Inc., Stryker Orthopaedics, and DePuy) research involvement are also observed to a lesser degree. By contrast, the highest number of optimized patent assignees are corporate entities, particularly those holding significant orthopedic market shares such as DePuy Orthopedics, Zimmer Holdings, and Smith & Nephew. Academic entities are a comparatively lower proportion (e.g. University College London, Mayo Foundation for Medical Education and Research, Massachusetts Institute of Technology).
implantation. Such delays are evident in comparative clinical usage rates of two bearing types against the publication activity.\(^5\)

On a more practical note, the contribution of data quality and availability on the assessment should be highlighted as well. For bibliometric records, database selection should be considered for journal indexing quality according to the bibliometric question to be answered. Some indicate higher importance on the international scale, with a greater propensity to exclude those publications which are in a more peripheral role (López-Illescas, De Moya Anegón, & Moed, 2009). Furthermore, the works in this analysis were limited to publications in English, possibly skewing results to English-speaking regions and the western world. As a result, the analysis may not be representative of works with regional emphasis not in the English language. Any updates on the records may affect the conclusion (such as inclusion of more translated works). Data associated with end-point impact would face similar obstacles, where availability comes with national and regional variation. The United States, a leading country in hip implant technology, established a nationalized data collection unit for joint replacements more recently in 2012. By contrast, Sweden has maintained the Swedish Hip Arthroplasty Register since 1979. To illustrate the coverage disparity, a retrospective review of hospital discharge records of the US between 2007–2014 indicated that discharges which included bearing surface codes accounted for 40.9–45.9\% of all discharges (Heckmann et al., 2018). In this case, the data is not fully comprehensive, with greater information breadth potentially presenting a challenge for larger countries with more diverse population.

**Conclusion**

Technological assessment is the evaluative process of a system as a whole. As such, the analysis should be approached from a framework according to both origins and outcomes. In this work, technological assessment is evaluated on the framework of a developmental life cycle. In the 28-year period of this analysis, the bibliometric evidence indicated an expanding research landscape in hip arthroplasty materials research. This was observed from publication productivity, unique publication sources, categorical diversity, and increasing country participation. Bibliometric indicators as outlined in this paper can be used as part of the evaluative process. However, one of the challenges with the assessment is maintaining neutrality in the evaluation. The selection of appropriate indicators in a technological assessment exercise should be evaluated according to the context of the application, requiring interpretation and subject area expertise, and guided by common reporting methodologies. Due to the academic publishing nature, bibliometrics is a favorable assessment tool when targeting systems whose mechanisms necessitate public reporting obligations (such as institutes with publicly funded research). From the private perspective, measurables arising from commercialization (such as patentometrics) may be better suited. Assessment of both public and private domains can maintain neutrality of the interpretation, owing to the multi-level nature of technology. Finally, in considering technology as an entirety, the

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**Figure F1:** An example of technological-clinical impact. National usage rates of hard/soft bearings (metal or ceramic with polyethylene) peaked in later years for the UK (data from National Joint Registry Report 2018), with ~90\% attributed usage in 2018. Hard/hard combinations enjoyed growth between 2006–2010 before dipping to less than 10\% of all totals. Early hard/hard growth (blue line) was attributed to metal-on-metal usage, followed by its obsolescence by 2012, after which the majority of rates are from ceramic-on-ceramic bearings exclusively. When comparing against polyethylene publication trends (bar plots), research output for the UK peaked in 2006. Between 2010–2017, publications appeared to stabilize, compared to the rising usage rates for the same period.
assessor should identify clearly the target aim of the technology to facilitate the additional measures to be included for
the analysis.

Funding Information
This work was funded by MOE RG 141/17.

Competing Interests
The authors have no competing interests to declare.

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