Corrosion, Tribology, and Tribocorrosion Research in Biomedical Implants: Progressive Trend in the Published Literature

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Abstract: (300 words)
Background: There has been significant progress in implant research during last the 10 years. The increase in the old age population coupled with a lack of proper physical activities is a potential causes for the sudden increment in the implant usages. However, implant life is limited due to the corrosion and tribocorrosion of implant materials. There is currently a large need for research in this area. Whether this need is being met or not has not been studied. Along this line, there has been no recent systematic approach made to analyze the progress of research and published work in this area. The objective of this work is to present the published literatures in the corrosion and tribocorrosion area during last century, giving more emphasize over last 10 years. The objective of this paper is to report the current status of the corrosion and tribocorrosion research in bio-implants based on the literature reviews. The review demonstrate that during last 10 years, there is a significant progress in the implant research, particularly in tribocorrosion research.

1. Introduction:

The research in tribology, corrosion and tribocorrosion field has increased in the last years due to their clinical relevance in orthopedic areas. As the number of publications parallels research activities, the degree of contribution to the literature for medical societies is regarded as a marker of clinical performance and research productivity. Several factors may contribute to the increase in the specific scientific output area. The most important is the need to bridge the knowledge gaps, particularly in the medical field, which is inevitably necessary for safer practice of medicine, academic performance improvement and better prospects for the patient. Scientific advances in the biomedical field are most likely to arise, or are most easily promoted, when

basic and clinical researchers are involved with the emergence and development of new contexts, creating a translational research.

The science of tribocorrosion can be defined as a degradation process of materials surface resulted from the combined action of mechanical wear and chemical/electrochemical reactions[1]. In other words, it is the correlated study of two different scientific domains, tribology and corrosion. Tribology is a branch of mechanical engineering, which consists in the study of interacting surfaces in relative motion, including the fields of friction, lubrication and wear. Corrosion is the deterioration process that converts the metal to a more stable form due to the chemical interaction of the material with its environment.

Orthopedic and dental implants experience the synergistic effect of wear and corrosion once they become load-bearing devices exposed to body fluids on the implant-bone interface. Body joints are influenced by periprosthetic fluid. It has been observed that bone-implant interfaces are subject to friction, which can cause fretting corrosion with inflammatory tissue reaction[2]. In respect to dental implants, they are in contact with a complex environment, the saliva, experiencing variations in pH and temperature that increases their corrosion process. Simultaneously, dental implants are exposed to cyclic micromovements at implant/abutment and implant/bone interface causing a relative motion between contacting surfaces, leading to wear[3,4]. Therefore, tribology and corrosion has been a major contributor to the premature non-success of implants and it is crucial to understand the tribocorrosion process on which the implants are submitted in order to avoid infection, necrosis, osteolysis and consequently, implant failure.

The number of total hip replacement and total knee replacement performed in 2010 accordingly to the Inpatient Surgery data from US were 332k and 719k, respectively[5]. These implants may last up to 12 years in average[3], however there is a history of failed innovations demonstrated by the failure or recall of some individual products, as well as whole classes of devices, such as metal-on-metal (MoM) bearings[6]. The concerns arise about the long-term

stability of MoM implants due to the release of metallic nanoparticles and ions, which had a carcinogenic potential, as well as associated hypersensitivity reactions, muscle and bone destruction and prosthetic loosening, leaving some patients with long-term disabilities[7,8].

Accordingly, to the American Academy of Implant Dentistry (AAID) 3 million have implants and that number is growing by 500,000 a year, with success rate of 98%[9]. The majority of failures are due to aseptic loosening and metal hypersensitivity[10,11]. This can be the result of chronic inflammatory response to implant surface debris and metal ions released from tribocorrosion process[12]. This demonstrates that previous tribocorrosion studies are fundamental to protect patients from increased risk associated with introduction of new technology and materials.

In fact, there has been significant progress in implant research during the last 10 years, mostly generated due to the problems found and the need to create new materials that can satisfy the required demands for each application. In order to analyze the progress of research and published work in the fields of corrosion, tribology and tribocorrosion related to orthopedic and dental implants, in this work we present an overview of the scientific development that occurred during the last 20 years as well as a future forecast growth in this research area based on the literature reviews.

2. Methods

In order to obtain the current research available on the field of implant tribocorrosion, the databases PubMed, Science Direct, Google Scholar, Scopus, Wiley Online, Web of Science, and Springer were searched for articles containing specified key words. Four types of searches were conducted in each of the databases mentioned. Results from each databases were placed into tables and when a search had been conducted on all databases, a final table was made containing the total findings from all databases. The implants of interest were divided into the categories dental, hip, knee, shoulder, TMJ, and spine. The articles found were then further divided into the fields of corrosion, tribology and tribocorrosion.

The first search looked for the total amount of articles available. In the databases, the key words used were one of keywords *Dental, Hip, Knee, Shoulder, TMJ,* or *Spine,* followed by keyword *Implant* followed by one of keywords *Corrosion, Tribology,* or *Tribocorrosion.* Each of the searches was in the form of *Dental Implant Corrosion* and the format of the search words are shown in figure 1. The number of articles from each database were recorded in tables in excel. A final table was made containing the totals from all the previous tables from each database (Table 1) for which a final bar graph was made (Figure 5).

The second search was to determine how the fields of corrosion, tribology and tribocorrosion on implants had progressed as a whole in the past 100 years. On each site, the key words *Implant AND (Tribocorrosion OR Corrosion OR Tribology)* were entered in order to obtain articles relating to implants and to any one of tribocorrosion, corrosion or tribology. A filter was applied to the search over the following time periods of 1900-1909, 1910-1919, 1920-1929, 1930-1939, 1940-1949, 1950-1959, 1960-1969, 1970-1979, 1980-1989, 1990-1999, 2000-2009, 2010-present. The format of the search is shown in figure 2. The data from each search was put into separate tables according to database. A final table was made containing the total articles for each time period from all the databases (Table 2). This final table's data was then converted into a bar graph (Figure 6).

The third search focused on how each individual types of implants had grown over the past ten years. Each type of implant (dental, hip, knee, shoulder, TMJ, spine) was searched over any of *Corrosion, Tribology,* or *Tribocorrosion*. The search was the filtered through the years 2005 through 2015. A sample search is *Dental AND Implant AND (Corrosion OR Tribology OR Tribocorrosion)* with a filter for a specified year such as 2005. The search format is shown in figure 3. Wiley online had an abnormally high value for the year of 2006 for all implants compared to the other databases. As such, the data from Wiley Online was discarded for this search. The data was entered into separate tables for each database and when all databases were searched, a final table was made containing the totals from all databases

(Table 3). Bar graphs were made to show the growth of all implants (Figure 7) as well as for each individual implant (Figures 8-13). Finally, linear models were made for each implant based on the years 2010-2015 that predict the growth for the research of each implant until 2020 (Figures 14-19).

The final search focused on how each subfield (corrosion, tribology, tribocorrosion) had grown over the past ten years. The keywords for this search were *Implant* followed by one of *Corrosion, Tribology* or *Tribocorrosion.* A filter was then applied for the years 2005 through 2015. A sample search is *Implant AND Corrosion* with a filter for the year 2005. The search format is shown in figure 4. The data was put into tables according to database with a final table made for the total of all databases (Table 4). A bar graph comparing the growth of all fields was made (Figure 20) as well as bar graphs which show the growth of each field individually (Figures 21-23). Finally, a linear model was made for each field based on the results for the years 2010-2015 that predict the growth of the research in each field until 2020 (Figures 24-26).

3. Results and Discussion

The graphs for the current articles on implant research showed the distribution of articles between different types of implants; dental, hip, knee, shoulder, TMJ, and spine implants. The implants with the most articles on them was dental with 31.0% of the articles followed by hip with 28.1%, knee with 17.3%, spine with 12.2%, shoulder with 10.4% and TMJ with 0.9% (Table 1). The number of articles on each implant is a good indicator of the relative importance given to each type of implants which might be directly correlated to the need for each type of implant. These results are supported by Figure 5 which gives the relative number of articles for each implant in the three fields.

The percentages for each of the fields were corrosion with 78.5%, tribology with 19.5% and tribocorrosion with 2% (Table 1). These results shows how the study of the wear of implants is being approached. From these percentages, it seems that the majority of the focus is on the

corrosion aspect of implants with some interest in tribology. Relatively few articles appear to take the interdisciplinary approach of tribocorrosion with implant research. This is shown in Figure 5 where the fields are shown in blue, red and green for the fields of corrosion, tribology and tribocorrosion respectively.

The timeline for published articles also gave interesting results. Up to the late 1960s, the number of articles published per time period remained relatively low and constant for all databases. However, after 1970, the number of articles published for each time period, seems to have been increasing exponentially. At present, the number of articles being published on the topic of tribocorrosion is greater than ever before. In just the time period from 2010-January 9, 2016, a greater number of articles has been published than the ten years prior (Figure 6). Some articles might be missing due to the lack of digitization of articles before 1960??? but this is not expected to be a major factor …..

The number of articles over the years has been steadily increasing as shown in Figure 7. However, from the year 2013 to 2014, the number of articles published has shown little growth. From the years 2014 to 2015, the number of articles actually seems to decrease. If the decrease from in published articles from the year 2014 to 2015 is an anomaly, the models for each implant based on the linear regression of the years 2010 to 2015 should be able to predict the growth of the research in these areas for the next three years as seen in Figures 8-13.

The articles published per year for each field over the last ten years shows the growth of the different types of tribocorrosion approaches as seen in Figure 14. The number of articles published per year on tribology only and corrosion only approaches have been steady with a slight decrease for the year 2015. However, the growth for articles published per year for the integrated approach with tribocorrosion has shown far greater growth than articles on single approaches (Figures 15-17).

5. Conclusions:

The amount of research being conducted on the tribocorrosion of implants of various sorts has been rapidly increasing over the years, especially in recent times. This can be associated in part to the growing need for implants due to the baby boomer generation growing older and thereby increasing the average age of the population. This large increase in the average age has led to a more people needing implants. Another contributing factor is the inactivity of the population as a whole. If this trend continues, the number of articles published per year will continue to increase.

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Keyword	Corrosion	Tribology	Tribocorrosion	Total Articles for Impant	Percentage
Dental Implants	37497	5165	669	43331	31.04518033
Hip Implants	27353	10728	1166	39247	28.11913394
Knee Implants	17119	6493	552	24164	17.31268001
Shoulder Implants	12113	2211	148	14472	10.36869331
TMJ Implants	914	320	43	1277	0.914926849
Spine Implants	14539	2372	172	17083	12.23938556
Total Articles for Field	109535	27289	2750	139574	
Percentage	78.47808331	19.55163569	1.970280998		

Table 1: Total number of published articles in the fields of corrosion, tribology and tribocorrosion related to six categories of implants

Time Period	# of Papers
before 1900	17
1900-1909	8
1910-1919	7
1920-1929	6
1930-1939	20
1940-1949	52
1950-1959	151
1960-1969	462
1970-1979	2676

1980-1989	7399
1990-1999	13459
2000-2009	36034
2010-present	43305

Table 2: Published articles in all of the fields of corrosion, tribology and tribocorrosion on implants over time periods of ten years

Year	Dental	Hip	Knee	Shoulder	TMJ	Spine
2005	1315	1230	775	400	18	672
2006	1699	1493	1010	759	77	810
2007	1752	1401	800	537	15	704
2008	2009	1477	946	575	56	737
2009	2104	1617	1001	679	26	793
2010	2478	1859	1266	736	46	969
2011	2774	2087	1331	812	48	1113
2012	3142	2354	1540	843	70	1254
2013	3732	3037	1859	1129	75	1443
2014	3981	3026	1884	1035	82	1451
2015	3928	2782	1685	944	75	1234

Table 3: Published articles on six categories of implant corrosion, tribology or tribocorrosion over time

Year	Corrosion	Tribology	Tribocorrosion
2005	3124	1030	25
2006	3795	1306	64
2007	4011	1267	40
2008	4267	1376	48
2009	4702	1453	71
2010	5326	1689	123
2011	6224	1949	162
2012	6963	2004	188
2013	8578	2573	344
2014	8981	2585	366
2015	8859	2344	422

Table 4: Published articles in the fields of corrosion, tribology and tribocorrosion on implants over time

List of Figure:

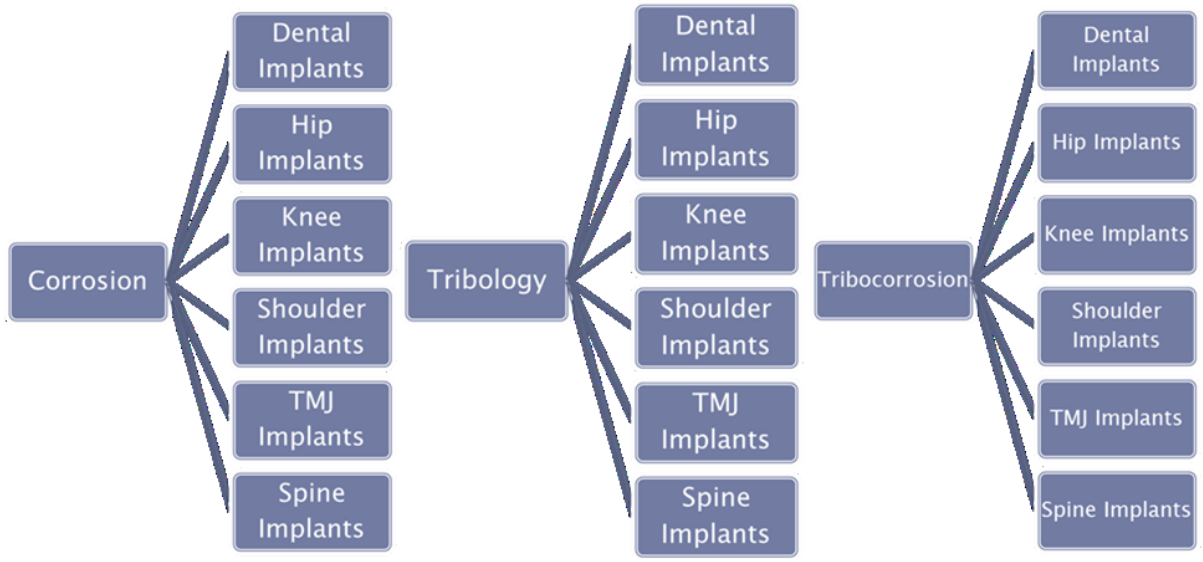

Figure 1: Flow chart that shows the key words and search methodology for total number of published articles in the fields of corrosion, tribology and tribocorrosion related to six categories of implants

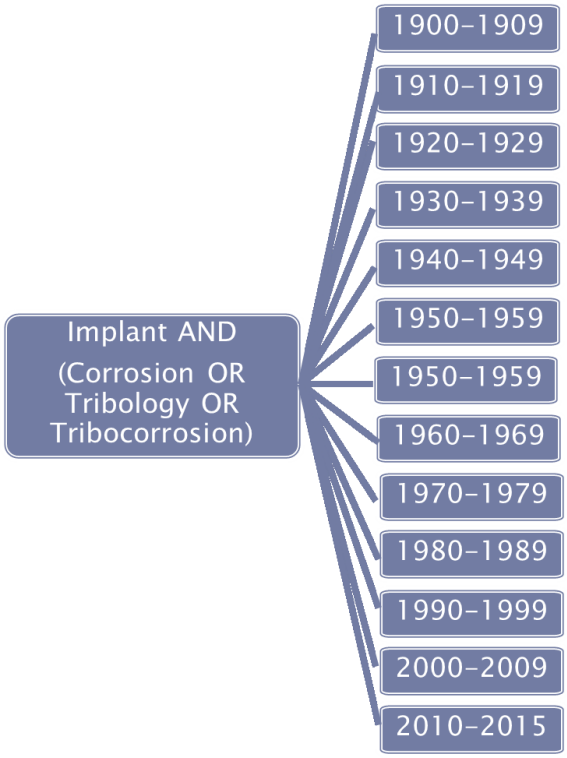

Figure 2: Flow chart that shows the key words and search methodology for published articles in all of the fields of corrosion, tribology and tribocorrosion on implants over time periods of ten years

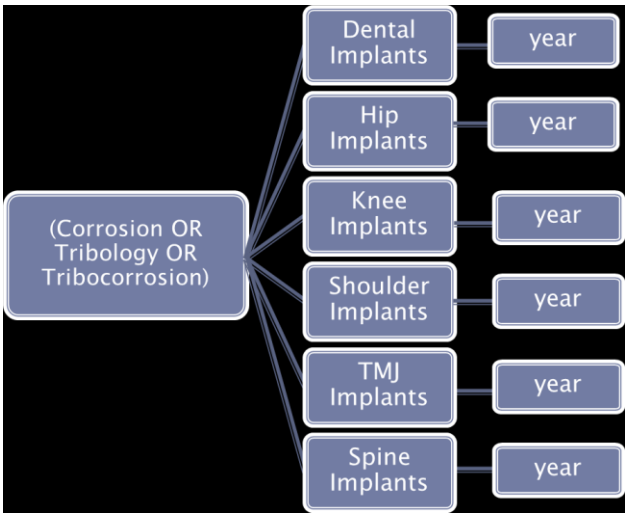

Figure 3: Flow chart that shows the key words and search methodology on published articles on six categories of implant corrosion, tribology or tribocorrosion over time

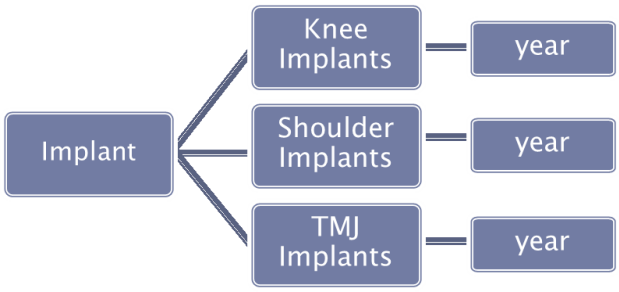

Figure 4: Flow chart that shows the key words and search methodology on published articles in the fields of corrosion, tribology and tribocorrosion on implants over time

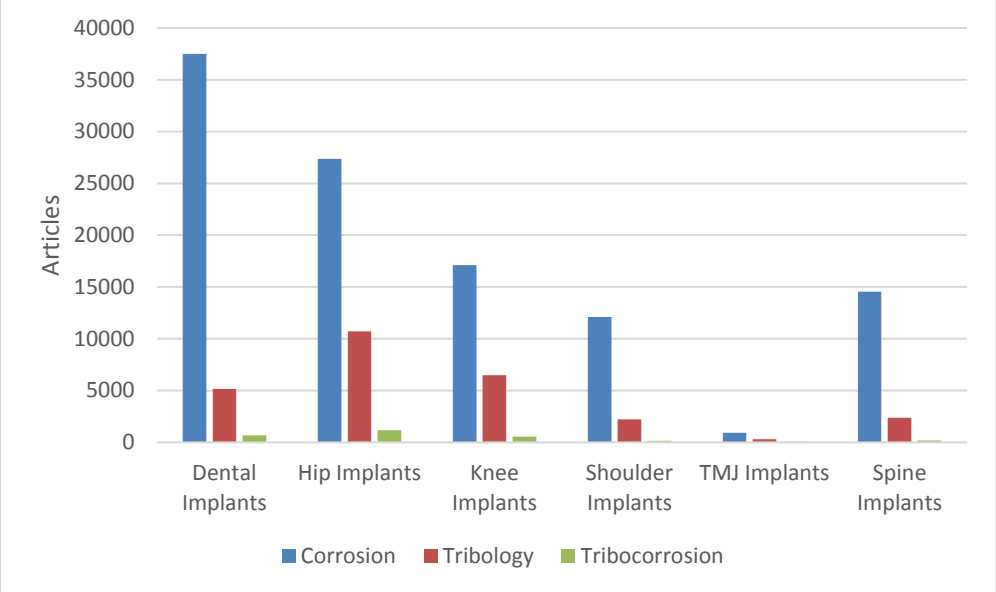

Figure 5: Total number of published articles in the fields of corrosion, tribology and tribocorrosion related to six categories of implants

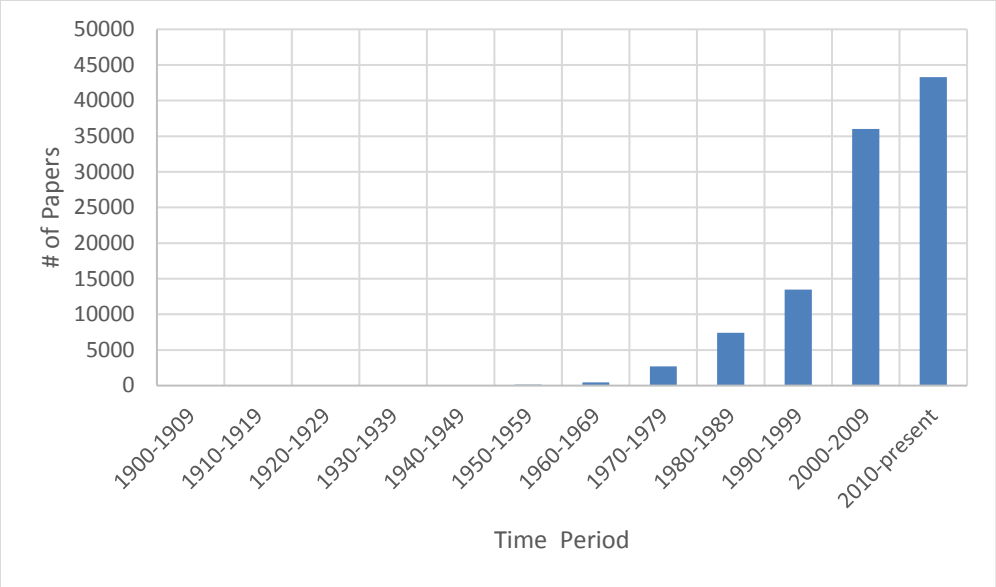

Figure 6: Published articles in all of the fields of corrosion, tribology and tribocorrosion on implants over time periods of ten years

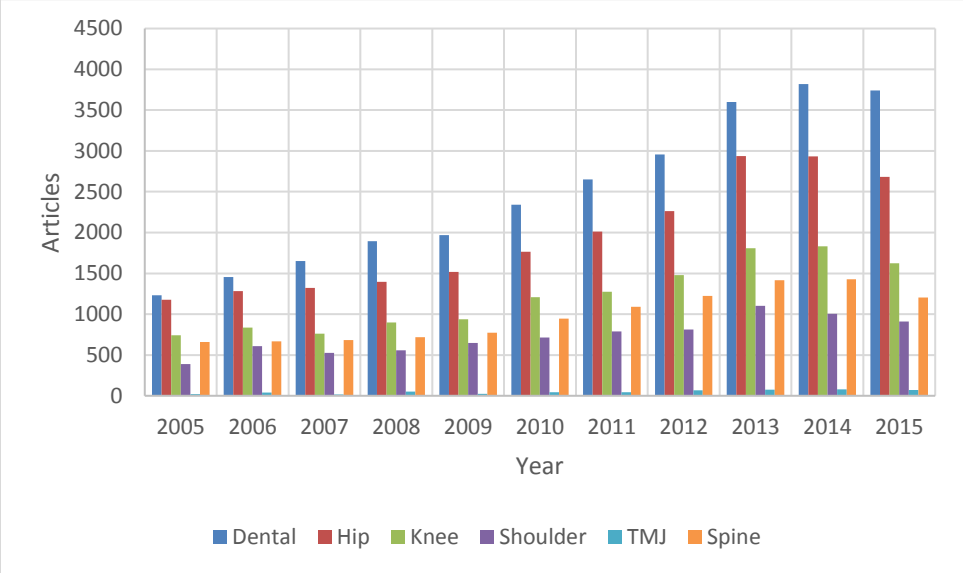

Figure 7: Published articles on six categories of implant corrosion, tribology or tribocorrosion over time

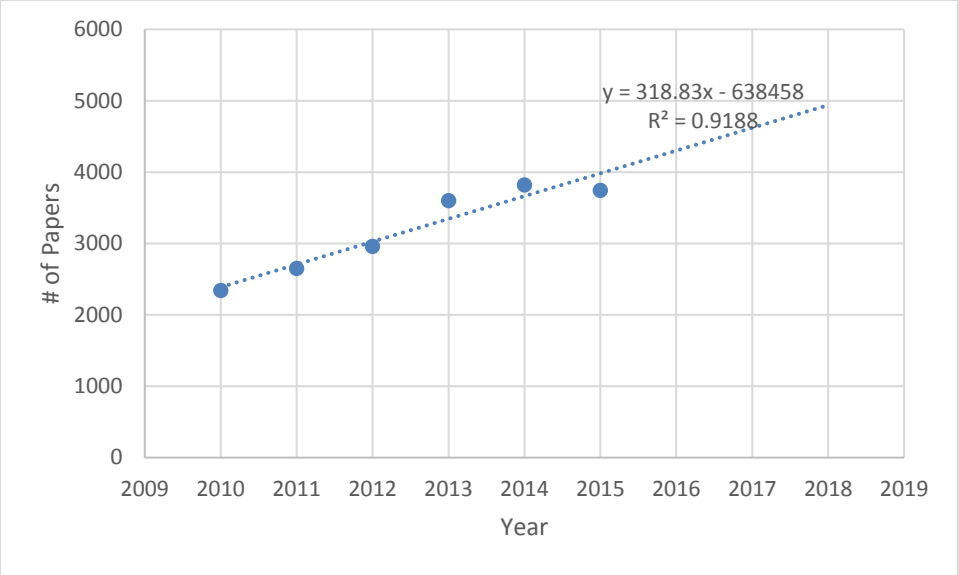

Figure 8: Projected growth of articles published on dental implant corrosion, tribology or tribocorrosion based on linear model

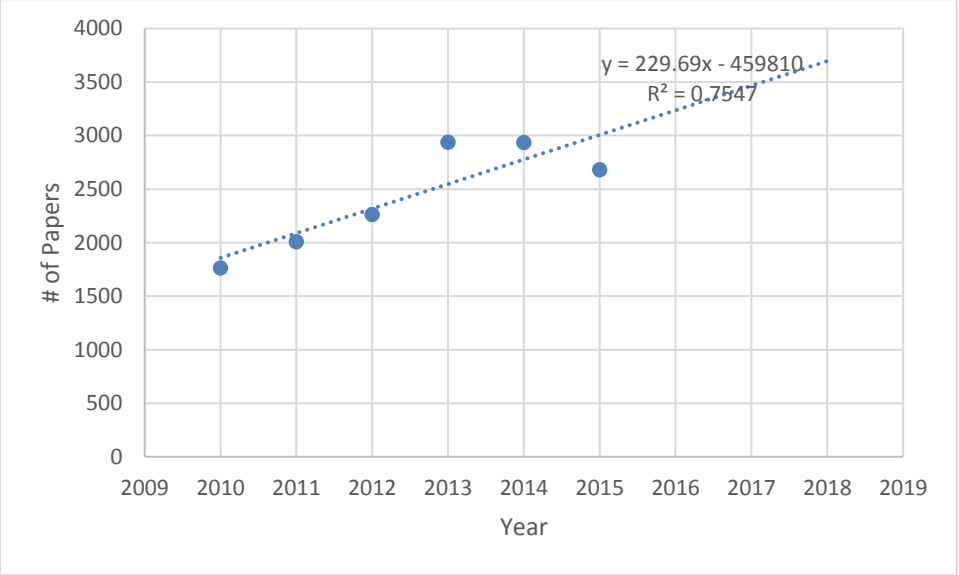

Figure 9: Projected growth of articles published on hip implant corrosion, tribology or tribocorrosion based on linear model

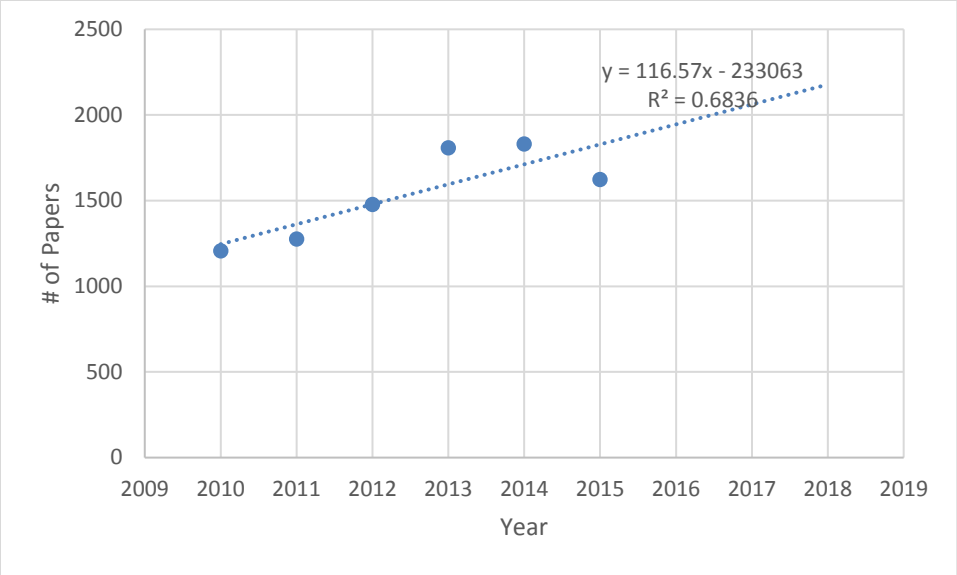

Figure 10: Projected growth of articles published on knee implant corrosion, tribology or tribocorrosion based on linear model

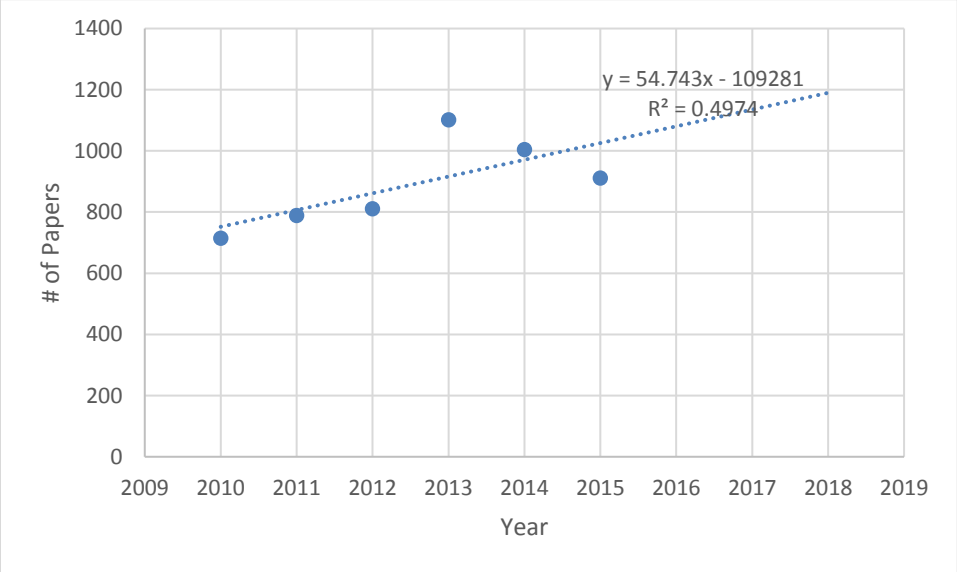

Figure 11: Projected growth of articles published on shoulder implant corrosion, tribology or tribocorrosion based on linear model

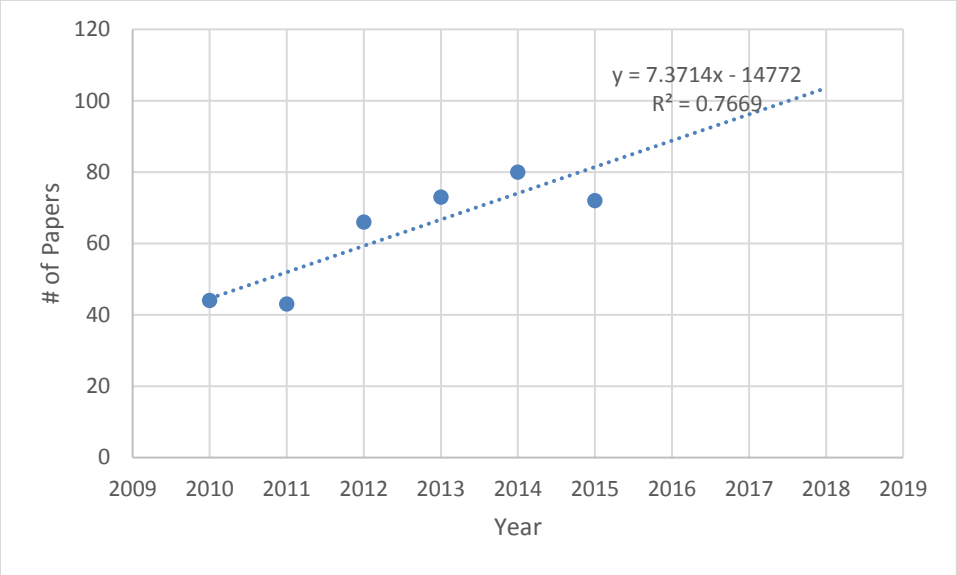

Figure 12: Projected growth of articles published on TMJ implant corrosion, tribology or tribocorrosion based on linear model

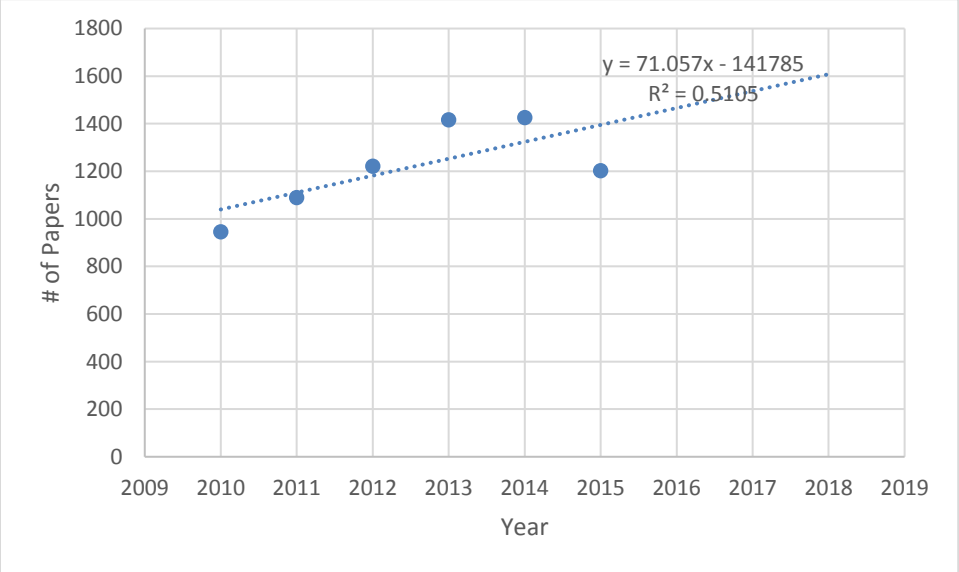

Figure 13: Projected growth of articles published on spine implant corrosion, tribology or tribocorrosion based on linear model

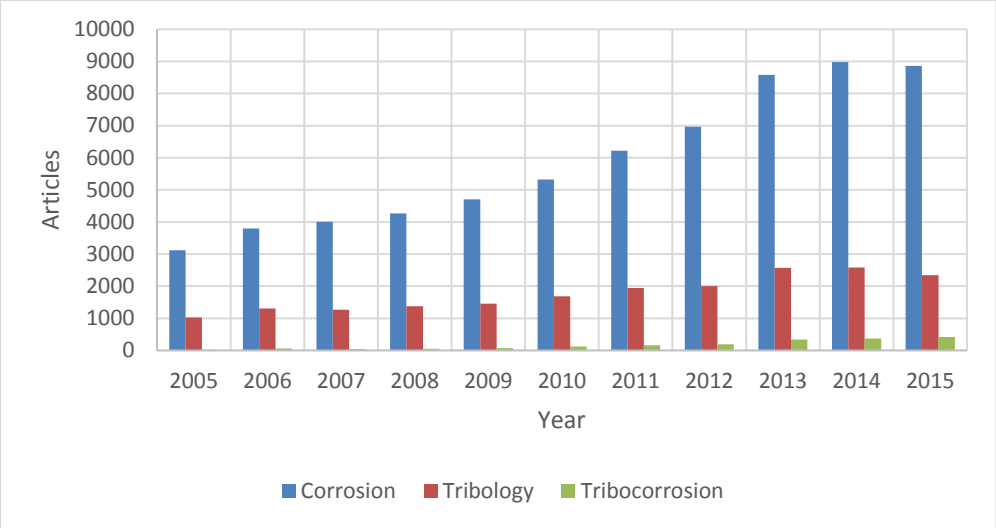

Figure 14: Published articles in the fields of corrosion, tribology and tribocorrosion on implants over time

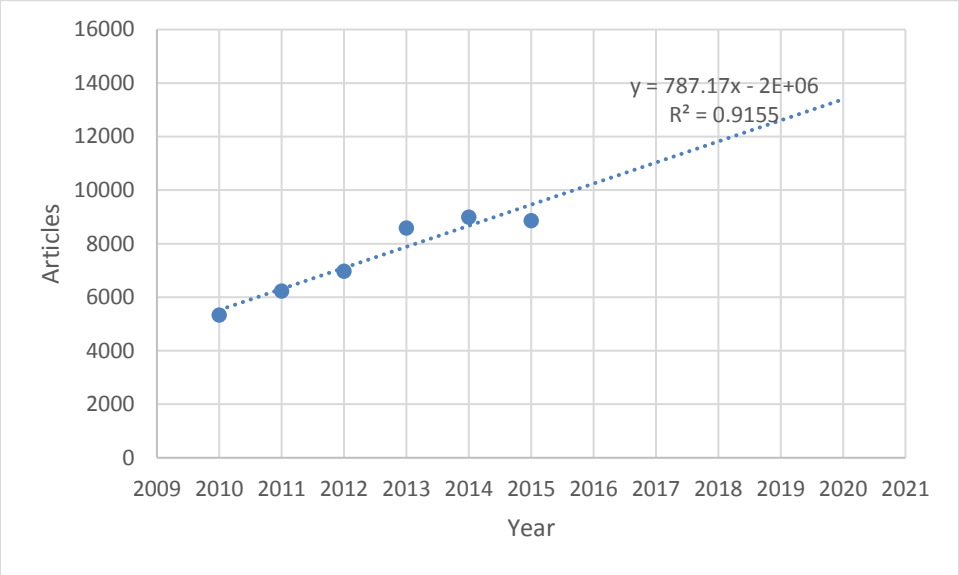

Figure 15: Projected growth of field of corrosion on implants for the next five years based on linear model

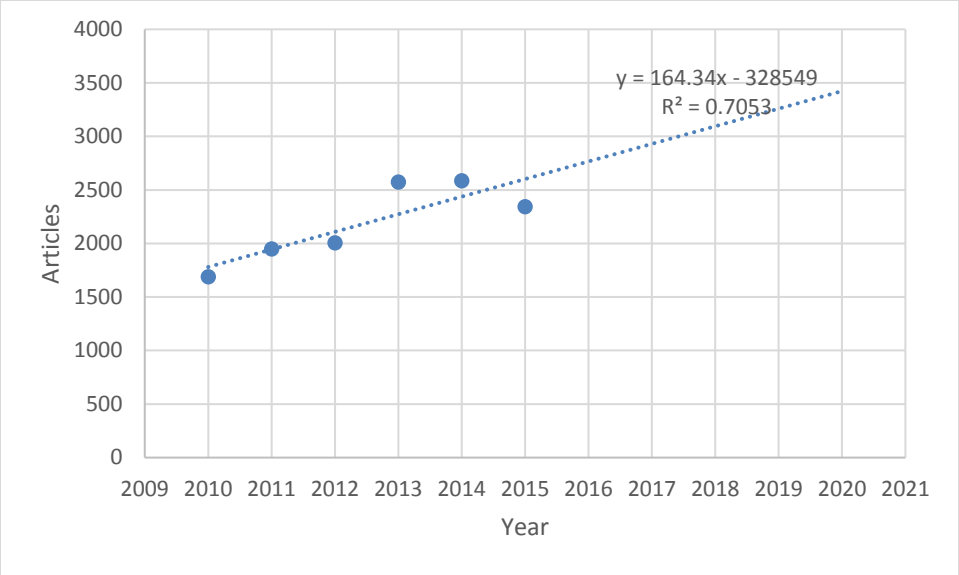

Figure 16: Projected growth of field of tribology on implants for the next five years based on linear model

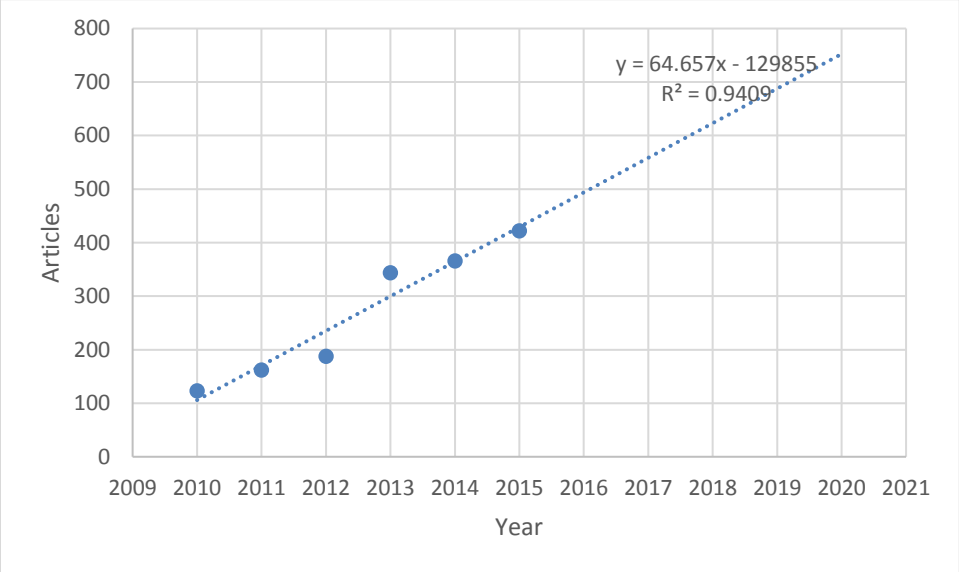

Figure 17: Projected growth of field of tribocorrosion on implants for the next five years based on linear model