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Highly Cited Publications in WoS, Biomedical Engineering in Science Citation Index Expanded:

A Bibliometric Analysis

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A R T I C L E I N F O

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A B S T R A C T

Identified and analyzed highly cited publications in the Web of Science category of biomedical engineering in the last three decades were investigated. Documents that have been cited more than 100 times from Web of Science Core Collection since publication year to the end of 2020 were defined as highly cited publications. The analyzed aspects covered document types, distribution of annual production and its citations per publication, journals, countries, institutes, authors, and the top cited articles. Publication performance of countries and institutions were evaluated by six publication indicators. Y-index was applied to evaluate authors' publication potential and their publication characteristics. Citation indicators including total citation and citations in 2020 were used to compare the most frequently cited articles. Results shows that most highly cited papers were published in journals with high impact factors. The USA dominated the six publication indicators. The G7 were ranked in the top ten productive countries. Eight of the top ten productive institutes were all located in USA. Results from Y-index shows that highly cited authors had higher proportion of corresponding-author articles and first-author articles. The article by Kokubo and Takadama in 2006 was the most frequently cited and the article by Litjens et al. in 2017 was the most impactful in 2020.

1. Introduction

In 1962, "The development of biomedical engineering" (Brewer et al., 1962) was presented by Brewer et al. Biomedical engineering, sometimes called bioengineering, includes all disciplines that combine engineering knowledge with biological and medical systems (Garfield, 1987). Biomedical engineering covers many different fields, such as agriculture and clinical engineering. Since the 1970s, clinical engineering has become a specialty of applying information generated by biomedical engineering (Oakes and Johns, 1973; Donahue and Sonnenburg, 1974). It also includes important management functions for hospitals, information systems, and healthcare delivery systems (Garfield, 1987).

One of the early fathers of biomedical engineering (Patterson, 2003), Otto Schmitt who created an excellent vector cardiographic lead system and could design very clever practical instruments such as the differential amplifier as well suggest and develop very advanced concepts. The earliest publications in the Web of Science category of biomedical engineering in the Science Citation Index Expanded were found in 1949, for example, the classic letter entitled "Brain stem reticular formation and

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activation of the EEG" (Moruzzi and Magoun, 1949) and highly cited article entitled "Diffuse projection systems: The integrative action of the thalamic reticular system" (Jasper, 1949).

In 2014, the highly cited publications with 100 citations or more from the Web of Science Core Collection since publication year to the end of the most recent year in the Web of Science category of health care sciences and services was proposed (Hsu and Ho, 2014). In recent years, highly cited publications in medical-related Web of Science categories were also concerned, including dentistry, oral surgery and medicine (Yeung and Ho, 2019), health policy and services (Hsu et al., 2020), emergency medicine (Ho, 2021), and anesthesiology (Juang et al., 2021). Publication performance of countries, and institutes with six publication indicators (Hsu and Ho, 2014) as well as three citation indicators were employed to characterize the highly cited articles. *Y*-index including two parameters was also used to evaluate authors' publication potential and publication characteristics.

In this study, highly cited publications in the Web of Science category of biomedical engineering in the Science Citation Index Expanded, having 100 citations or more were characterized and examined.

2. Materials and Methods

The data is taken from Clarivate Analytics' Web of Science Core Collection of Science Citation Index Expansion (SCI-EXPANDED), last updated on October 25, 2021. The 2020 Journal Impact Factor (IF_{2020}) is reported in the Journal Citation Report (JCR) on June 30, 2021. According to the definition of journal impact factor, it is suggested to retrieve the documents published in 2020 from SCI-EXPANDED after IF_{2020} is reported. According to the 2020 Journal Citation Report (JCR), it has included a citation index for 9,531 journals in 178 Web of Science categories in SCI-EXPANDED. In 2020, 90 journals were classified in the Web of Science category of biomedical engineering. From 1991 to 2020, a total of 251,537 documents including 217,960 articles were retrieved based on the category of biomedical engineering.

2.1. Three Citation Indicators are Used to Characterize Highly Cited Articles

TC_{year} was proposed in 2011 (Wang et al., 2011; Chuang et al., 2011), is the number of citations from the Web of Science Core Collection since publication year to the end of the most recent year. For example, TC_{2020} represents the number of citations from publication year to the end of 2020. C_{year} is proposed by Ho (2012) and is the number of citations in the most recent year. For example, C_{2020} represents the number of citations in 2020. CPP_{year} is the number of citations per article ($CPP_{year} = TC_{year}/TP$) is also applied (Ho, 2012) (*TP*: total number of articles). In 2014, highly cited publications with TC_{year} of 100 or more were proposed by Ho's group (Ho, 2014; Ho and Kahn, 2014; Hsu and Ho, 2014). All document information from SCI-EXPANDED has been checked and downloaded to Microsoft Excel 2016 for manual analysis (Li and Ho, 2008; Ho, 2021). The journal impact factor (IF_{2020}) of each journal is taken from the 2020 Journal Citation Reports (JCR).

In the SCI-EXPANDED database, the corresponding author is labeled as reprint author, but in this study, we used the term corresponding author (Ho, 2012). In multi-corresponding author articles, only the last corresponding author, institute, and country were considered (Ho, 2019). In a single-author article and single-institute article where authorship and affiliation are unspecified in SCI-EXPANDED, the single author and single institute are both the first and corresponding author and institute, respectively (Ho, 2014). Affiliations in England, Scotland, Northern Ireland, and Wales were reclassified as being from the United Kingdom (UK) (Chiu and Ho, 2005). Affiliations in Hong Kong before 1997 were reclassified as being from China (Chuang et al., 2011). Affiliations in USSR were checked and reclassified as being from Russia. Six publication indicators were applied to evaluate the publication performance of countries and institutions (Hsu and Ho, 2014):

- TP: total number of articles
- IP: number of single-country or single-institution authored articles
- CP: number of internationally or inter-institutionally collaborative articles
- FP: number of first-author articles
- RP: number of corresponding-author articles
- SP: number of single-author articles

Y-index was used to evaluate the publication performance of authors. The *Y*-index is defined as (Ho, 2012; 2014) *Y*-index = j h, where j is a constant related to the publication potential, the sum of the first-author articles and the corresponding-author articles; and h is a constant related to the publication characteristics, polar angle about the proportion of *RP* to *FP*. The greater the value of j, the more the first- and corresponding-author contributes to the articles.

- h = π/2, indicates an author that has only published corresponding-author articles, j is the number of corresponding-author articles;
- π/2 > h > 0.7854 indicates that an author has more corresponding-author articles than first-author articles (FP > 0);
- h = 0.7854 indicates that an author has the same number of first- and corresponding-author articles (FP > 0 and RP > 0);
- 0.7854 < h < 0 indicates an author with more first-author articles than corresponding-author articles (RP > 0);
- h = 0, indicates that an author has only published first-author articles, j is the number of first-author articles.

3. Results & Discussion

3.1. Document Type and Language of Publication

A total of 11,905 highly cited publications (4.7% of 251,537 documents in the Web of Science category of biomedical engineering in SCI-EXPANDED) with TC_{2020} of 100 or more from 1991 to 2020 were found including 10,674 highly cited articles (4.9% of 217,960 articles). Among them, 114 classic publications (0.045% of 251,537 documents) with $TC_{2020} \geq 1{,}000$ (Long et al., 2014) including 74 articles, 38 reviews, four proceedings papers, three book chapters, one editorial material, and one letter. The percentage of highly cited documents in the category of biomedical engineering (4.7%) was higher than medical-related categories, for example health care sciences and services (0.68%) (Hsu and Ho, 2014), and emergency medicine (0.95%) (Ho, 2021), and anesthesiology (2.2%) (Juang et al., 2021). Similarly, the percentage of highly cited articles in the category of biomedical engineering (4.9%) was also higher than medical-related categories, for example emergency medicine (0.95%) (Ho, 2021), dentistry, oral surgery and medicine (1.8%) (Yeung and Ho, 2019) and anesthesiology (3.7%) (Juang et al., 2021).

As the basic idea of scientific results, which can be repeated and checked, Ho's group proposed citation indicator TC_{year}, the number of citations from Web of Science Core Collection since publication year to the end of the most recent year (Wang et al., 2011) and citations per publication (CPP_{year} = TC_{year}/TP) (Fu et al., 2012). Analysis of document types and their citations per publication (CPP_{year}) as well as the number of authors per publication (*APP*) was proposed in 2017 (Monge-Nájera and Ho, 2017). Table 1 shows the characteristics of the nine document types with the total number of publications (*TP*), *APP*, and CPP_{2020}. Document type of articles was the most popular with 10,674 articles (90% of 11,905 highly cited documents) and the *APP* of 5.0.

Table 1
Citations and authors according to the document type

Document type	TP	%	AU	APP	TC_{2020}	CPP_{2020}
Article	10,674	90	53,296	5.0	2,063,273	193
Review	1,150	10	3,951	3.4	343,407	299
Proceedings paper	441	3.7	1,888	4.3	89,928	204
Book chapter	96	0.81	262	2.7	28,987	302
Note	46	0.39	147	3.2	7,892	172
Editorial material	28	0.24	84	3.0	6,893	246
Letter	6	0.050	25	4.2	2,257	376
Correction	1	0.0084	1	1.0	120	120
Retracted publication	1	0.0084	12	12	115	115

TP: total number of highly cited publications; %: percentage of publications in all highly cited documents; *AU*: number of authors; *APP*: number of authors per publication (*AU*/*TP*); TC_{2020}: total number of citations from Web of Science Core Collection since publication year to the end of 2020; CPP_{2020}: citations per publication (TC_{2020}/TP).

The document type of letters with six documents had the highest CPP_{2020} with 376. In total, 1,150 highly cited reviews were published in 76 journals, mainly in *Biomaterials* (807 reviews; 18% of 1,150 reviews) with a CPP_{2020} of 487 and an *APP* of 3.4, followed by *Annual Review of Biomedical Engineering* (154; 13%) with a CPP_{2020} of 323 and an *APP* of 2.7 and *Acta Biomaterialia* (114; 10%) with a CPP_{2020} of 260 and an *APP* of 3.6. It has been noticed that documents could be classified within two document types in Web of Science, resulting in the sum of percentages greater than 100% in Table 1 (Usman and Ho, 2020). For example, 441 documents were classified in both document types of articles and proceedings papers.

Only document type of articles was considered for further analysis because they include more complete information such as introduction, method, results, discussion, and conclusions (Ho et al., 2010). In the last three decades, 10,674 highly cited articles were identified in the Web of Science category of biomedical engineering in SCI-EXPANDED. Only one highly cited article was published in German in the *Biomedizinische Technik* and one in the *Cardiovascular Engineering* was recorded as unspecified.

3.2. Publication Distribution

A relationship between the annual number of highly cited articles (*TP*) and their citations per publication (CPP_{year} = TC_{year}/TP) by the years (Ho, 2013) in a research topic has been proposed. It was used in the medical-related Web of Science categories, for example, dentistry, oral surgery and medicine (Yeung and Ho, 2019), emergency medicine (Ho, 2021), and anesthesiology (Juang et al., 2021). A total of 10,674 highly cited articles in the category of biomedical engineering were found from 1991 to 2020 with a total TC_{2020} of 2,063,273 with an average of 193 and the maximum value of TC_{2020} was 5,260. Figure 1 shows the distribution of the 10,674 highly cited articles over the years and their CPP_{2020}. Time is one of the reasons to accumulate citations for an article. The most highly cited articles were found in 2020 with 735 articles. In general, a decade was needed to accumulate citations of TC_{2020} of 100 in the Web of Science category of biomedical engineering. However, the contribution of an article is another reason to be highly cited. The only one highly cited article with a TC_{2020} of 102 was found in the most the recent year of 2020, entitled "Covid-19: Automatic detection from X-ray images utilizing transfer learning with convolutional neural networks" (Apostolopoulos and Mpesiana, 2020) in *Physical and Engineering Sciences in Medicine*. Apostolopoulos and Mpesiana from the University of Patras in Greece concluded that using Deep Learning with X-ray imaging to extract important biomarkers related to Covid-19 disease so that the medical community can evaluate the possibility of including X-rays in disease diagnosis. A smooth increase of CPP_{2020} was found from 2020 to 2006 but 2018, 2017, and 2016 which can be attributed to the top highly cited article by Litjens et al. (2017) with a TC_{2020} of 2,452 and Shin, et al., (2016) with a TC_{2020} of 1,557.

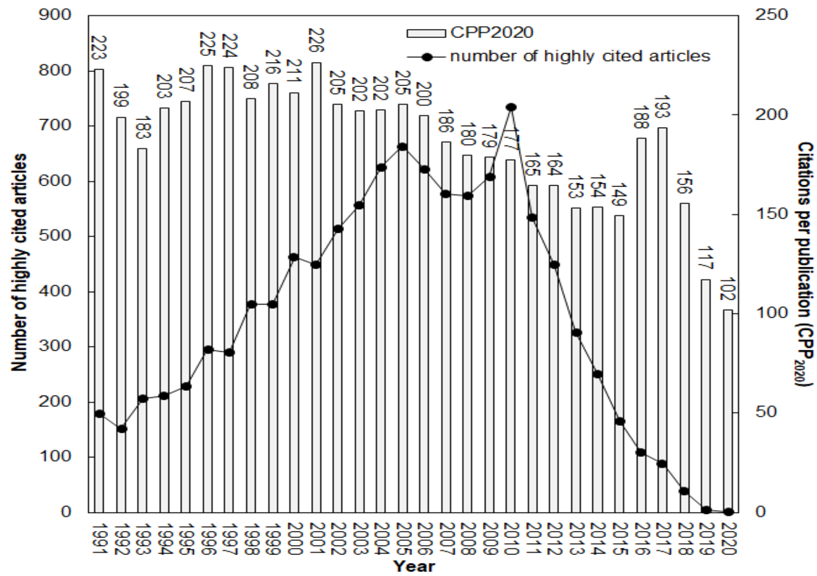

Fig. 1. Number of highly cited articles and citations per publication by year

3.3. Journals

A total of 90 journals were classified under the Web of Science category of biomedical engineering in 2020. The 9,692 highly cited articles were published in 67 of these journals (74% of 90 journals). Other 982 highly cited articles were published in 28 biomedical engineering journals that were no longer tracked by the Web of Science category of biomedical engineering as of 2020. Table 2 shows the top ten productive journals with their IF_{2020}, *APP*, and CPP_{2020}. Biomaterials with an IF_{2020} of 12.479 (ranked 3rd in biomedical engineering) published one-third of highly cited articles. Fifty-one percent of the highly cited articles were published in the top four journals: the Biomaterials (3,535 articles; 33% of 10,674 articles), the *Journal of Biomechanics* (721; 6.8%) with an IF_{2020} of 2.712 (ranked 57th), the *IEEE Transactions on Medical Imaging* (651; 6.1%) with an IF_{2020} of 10.048 (ranked 6th), and the *Journal of Biomedical Materials Research* (590 articles from 1991 to 2002; 5.5%) with an IF_{2004} of 3.652. After 2002, the *Journal of Biomedical Materials Research* was divided to be two journals: the *Journal of Biomedical Materials Research Part A* with an IF_{2020} of 4.396 had 312 highly cited articles, and the *Journal of Biomedical Materials Research Part B-Applied Biomaterials* with an IF_{2020} of 3.368 had 91 highly cited articles. Compare to the top ten productive journals in Table 2, the *Biomaterials* not only published the most highly cited articles but also had the highest *APP* of 5.7 in the category of biomedical engineering. The *IEEE Transactions on Medical Imaging* had the highest CPP_{2020} of 243 while the *Journal of Biomedical Materials Research Part A* with a CPP_{2020} of 162. A total of 19 highly cited articles were published in the *Nature Biomedical Engineering* with the highest IF_{2020} of 25.671 in the category of biomedical engineering in 2020. However, the *Bioactive Materials* (IF_{2020} = 14.593, ranked 2nd) with 3 highly cited reviews, the *Bioengineering & Translational Medicine* (IF_{2020} = 10.711, ranked 4th) with 3 highly cited reviews, and the *NPJ Regenerative Medicine* (IF_{2020} = 10.364, ranked 5th) without any highly cited publications. The *Journal of Medical Devices-Transactions of the ASME* had the lowest IF_{2020} of 0.582 (ranked 87th of the 90 journals) and published one highly cited article with CPP_{2020} of 112.

Table 2
Top 10 productive journals with highly cited articles in the Web of Science category of biomedical engineering.

Journal	TP (%)	IF_{2020} (R)	APP	CPP_{2020}
Biomaterials	3,535 (33)	12.479 (3)	5.7	201
Journal of Biomechanics	721 (6.8)	2.712 (57)	3.7	184
IEEE Transactions on Medical Imaging	651 (6.1)	10.048 (6)	4.7	243
Journal of Biomedical Materials Research	590 (5.5)	3.652* (N/A)	4.7	211
IEEE Transactions on Biomedical Engineering	531 (5.0)	4.538 (24)	3.9	200
Physics in Medicine and Biology	508 (4.8)	3.609 (40)	4.8	200
Acta Biomaterialia	440 (4.1)	8.947 (10)	5.6	169
Clinical Oral Implants Research	377 (3.5)	5.977 (17)	4.5	176
Journal of Biomedical Materials Research Part A	312 (2.9)	4.396 (25)	5.1	162
Annals of Biomedical Engineering	204 (1.9)	3.934 (31)	4.0	163

TP: total number of highly cited articles; IF_{2020}: journal impact factor for 2020; *R*: rank in Web of Science category of biomedical engineering in 2020; *: journal impact factor for 2004 (IF_{2004}); *APP*: number of authors per publication; CPP_{2020} citations per publication (TC_{2020}/TP).

3.4. Countries, Institutions, and Authors

There were 10,669 highly cited articles (99.95% of 10,674 highly cited articles) with author affiliation information in SCIEXPANDED from 75 countries. A total of 8,273 (78% of 10,669 articles) were single-country articles from 52 countries and 2,396 (22%) were internationally collaborative articles from 73 countries. Six publication indicators (Ho and Kahn, 2014; Hsu and Ho, 2014) and a citation indicator, CPP_{2020} (Ho, 2019) were applied to compare the top ten productive countries (Table 3). The top 10 most productive countries published 8,978 articles (84% of the 10,669 articles) with TC_{2020} of 1,740,884 (84% of TC_{2020} of 2,063,273). All of the seven major industrialized countries of the world (G7) including the USA, Italy, the UK, Japan, Canada, France, and Germany were ranked in the top 10. Six European countries, two American countries, and two Asia countries were ranked in the top 10 publications. Australia with 296 highly cited articles ranked 12nd and South Africa with 12 highly cited articles ranked 40th was the most productive country in Africa. The USA dominated in the six publication indicators with a *TP* of 4,621 highly cited articles (43% of 10,669 highly cited articles), an *IP* of 3,384 articles (41% of 8,273 single-country articles), a *CP* of 1,237 articles (52% of 2,396 internationally collaborative articles), an *FP* of 4,032 articles (38% of 10,669 first-author articles), an *RP* of 3,853 articles (37% of 10,344 corresponding-author articles), and an *SP* of 140 articles (45% of 309 single-author articles). The UK, Switzerland, and the Netherlands had higher CPP_{2020} of 206, 204, and 202, respectively while China and Italy had CPP_{2020} of 181 and 174, respectively.

Table 3
Top 10 most productive countries.

Country	TP	TPR (%)	IPR (%)	CPR (%)	FPR (%)	RPR (%)	SPR (%)	CPP_{2020}
USA	4,621	1 (43)	1 (41)	1 (52)	1 (38)	1 (37)	1 (45)	198
China	1,156	2 (11)	2 (9.1)	2 (17)	2 (8.9)	2 (9.0)	15 (1.0)	181
UK	870	3 (8.2)	3 (5.8)	3 (16)	3 (6.0)	3 (6.1)	2 (10)	206
Germany	795	4 (7.5)	5 (5.0)	4 (16)	4 (5.5)	4 (5.6)	5 (4.2)	195
Japan	631	5 (5.9)	4 (5.2)	9 (8.5)	5 (4.7)	5 (4.7)	4 (4.5)	193
Netherlands	573	6 (5.4)	7 (3.7)	6 (11)	6 (4.2)	6 (4.2)	6 (3.6)	202
Canada	557	7 (5.2)	6 (4.1)	7 (9.2)	7 (4.0)	7 (4.0)	3 (7.1)	191
Switzerland	483	8 (4.5)	11 (2.2)	5 (12)	9 (2.8)	9 (2.9)	8 (2.6)	204
Italy	441	9 (4.1)	8 (2.8)	8 (8.8)	8 (2.9)	8 (2.9)	15 (1.0)	174
France	405	10 (3.8)	10 (2.5)	10 (8.1)	10 (2.7)	10 (2.7)	9 (1.9)	199

TP: total number of highly cited articles; *TPR* (%): rank and the percentage of total articles; *IPR* (%): rank and percentage of single-country articles in all single-country articles; *CPR* (%): rank and percentage of internationally collaborative articles in all internationally collaborative articles; *FPR* (%), rank and the percentage of first-author articles in all first-author articles; *RPR* (%), rank and the percentage of the corresponding-authored articles in all corresponding-authored articles; *SPR* (%), rank and the percentage of the single-author articles in all single-author articles; CPP_{2020}: citations per publication (TC_{2020}/TP).

In total, 4,323 highly cited articles (41% of 10,669 highly cited articles) were single-institute articles and 6,346 (59%) were inter-institutionally collaborative articles. Six publication indicators (Ho, 2014) and citation indicator, CPP_{2020} (Ho, 2019) were applied to compare the top 22 institutes with 100 highly cited articles or more (Table 4). Thirteen of the top 22 institutes were located in the USA, two in China and the UK, respectively, and one in each of Canada, Japan, Netherlands, Singapore, and Switzerland, respectively. The Harvard University in the USA ranked top in two publication indicators with a *TP* of 320 highly cited articles (3.0% of 10,669 highly cited articles) and a *CP* of 289 articles (4.6% of 6,346 inter-institutionally collaborative articles). The University of Michigan in the USA dominated in the two publication indicators with an *IP* of 115 articles (2.7% of 4,323 single-institute articles) and an *SP* of seven articles (2.3% of 309 single-author articles). The Chinese Academy of Sciences in China ranked top in two publication indicators with an *FP* of 168 articles (1.6% of 10,669 first-author articles) and an *RP* of 167 articles (1.6% of 10,344 corresponding-author articles). Articles published by the University of Texas in the USA had the highest CPP_{2020} of 285 while the Shanghai Jiao Tong University in China, the Chinese Academy of Sciences in China, and the University of Toronto in Canada had CPP_{2020} of 179, 173, and 169, respectively.

Table 4
Top 22 most productive institutes with 100 or more highly cited articles in the Web of Science Category of Biomedical Engineering.

Institute	TP	TPR (%)	IPR (%)	CPR (%)	FPR (%)	RPR (%)	SPR (%)	CPP_{2020}
Harvard University, USA	320	1 (3.0)	24 (0.72)	1 (4.6)	6 (1.0)	7 (0.94)	24 (0.65)	228
Massachusetts Institute of Technology (MIT), USA	261	2 (2.4)	13 (0.86)	2 (3.5)	4 (1.2)	4 (1.1)	3 (1.6)	225
Chinese Academy of Sciences, China	242	3 (2.3)	8 (1.2)	3 (3.0)	1 (1.6)	1 (1.6)	N/A	173
University of Michigan, USA	221	4 (2.1)	1 (2.7)	6 (1.7)	2 (1.5)	2 (1.5)	1 (2.3)	215
National University of Singapore, Singapore	190	5 (1.8)	2 (1.8)	5 (1.7)	3 (1.3)	3 (1.4)	12 (1.0)	255
Stanford University, USA	156	6 (1.5)	12 (1.0)	4 (1.8)	11 (0.82)	11 (0.81)	24 (0.65)	209
University of Pennsylvania, USA	144	7 (1.3)	3 (1.5)	18 (1.2)	8 (0.95)	6 (0.95)	12 (1.0)	217
University of Texas, USA	144	7 (1.3)	9 (1.1)	7 (1.5)	14 (0.77)	15 (0.7)	57 (0.32)	285
University of Washington, USA	139	9 (1.3)	6 (1.5)	20 (1.2)	7 (1.0)	8 (0.92)	2 (1.9)	189
University of Pittsburgh, USA	135	10 (1.3)	3 (1.5)	22 (1.1)	5 (1.0)	5 (1.0)	9 (1.3)	183
University of California San Diego, USA	128	11 (1.2)	11 (1.0)	14 (1.3)	13 (0.79)	13 (0.76)	3 (1.6)	200
Kyoto University, Japan	126	12 (1.2)	5 (1.5)	28 (1.0)	9 (0.93)	9 (0.87)	12 (1.0)	215
University of Toronto, Canada	126	12 (1.2)	7 (1.3)	21 (1.1)	12 (0.81)	12 (0.78)	12 (1.0)	169
Rice University, USA	123	14 (1.2)	16 (0.79)	8 (1.4)	10 (0.83)	10 (0.82)	N/A	215
Georgia Institute of Technology, USA	119	15 (1.1)	19 (0.76)	11 (1.4)	15 (0.75)	14 (0.73)	3 (1.6)	199
University of Bern, Switzerland	116	16 (1.1)	31 (0.62)	8 (1.4)	20 (0.58)	21 (0.58)	N/A	219
Johns Hopkins University, USA	114	17 (1.1)	16 (0.79)	16 (1.3)	18 (0.62)	18 (0.61)	N/A	184
University of London Imperial College of Science, Technology and Medicine, UK	113	18 (1.1)	22 (0.74)	15 (1.3)	17 (0.67)	17 (0.66)	3 (1.6)	205
UCL, UK	108	19 (1.0)	38 (0.51)	11 (1.4)	21 (0.57)	19 (0.59)	N/A	183
University of Twente, Netherlands	108	19 (1.0)	38 (0.51)	11 (1.4)	22 (0.56)	22 (0.54)	N/A	196
Shanghai Jiao Tong University, China	102	21 (1.0)	64 (0.32)	10 (1.4)	32 (0.45)	39 (0.40)	N/A	179
Columbia University, USA	100	22 (0.94)	19 (0.76)	23 (1.1)	19 (0.60)	19 (0.59)	57 (0.32)	192

TP: total number of highly cited articles; *TPR* (%): rank and the percentage of total articles; *IPR* (%): rank and percentage of single-institute articles in all single-institute articles; *CPR* (%): rank and percentage of inter-institutionally collaborative articles in all inter-institutionally collaborative articles; *FPR* (%): rank and the percentage of first-author articles in all first-author articles; *RPR* (%): rank and the percentage of the corresponding-author articles in all corresponding-author articles; *SPR* (%), rank and the percentage of single-author articles in all single-author articles; N/A: not available; CPP_{2020}: citations per publication (TC_{2020}/TP).

The *Y*-index indicator is related to the number of first-author highly cited articles (*FP*) and corresponding-author highly cited articles (*RP*) (Ho, 2012; 2014). The *Y*-index combines two parameters (*j*, *h*) to assess both the publication potential and the characteristics of the contribution as a single index. The indicator has also been applied to compare highly cited authors in medical-related Web of Science categories: health care sciences and services (Hsu and Ho, 2014), dentistry, oral surgery and medicine (Yeung and Ho, 2019), health policy and services (Hsu et al., 2020), emergency medicine (Ho, 2021), and anesthesiology (Juang et al., 2021).

In total, 10,161 (95% of 10,674 articles) highly cited articles in the Web of Science category of biomedical engineering with both first and corresponding-author information was used to calculate *Y*-index for authors. A total of 10,161 highly cited articles were contributed by 29,119 authors: 16,596 authors (68% of 29,119 authors) did not have first- or corresponding-author articles with *Y*-index = (0, 0); 1,855 (6.4%) authors only published corresponding-author articles with $h = \pi/2$; 492 (1.7%) authors published more corresponding-author articles than first-author articles with $\pi/2 > h > 0.7854$; 3,441 (12%) authors published the same number of first- or corresponding-author articles with $h = 0.7854$; 282 (1.0%) authors published more first-author articles than corresponding-author articles with $0.7854 > h > 0$; and 3,351 (12%) authors only published first-author articles with $h = 0$.

Figure 2 shows the distribution of the *Y*-index (*j*, *h*) of the top 20 highly cited authors with *j* of 22 or more. Each dot represents one value that could be one author or many authors (Ho, 2014), for example, A.J. Garcia and C.T. Laurencin with *Y*-index = (23, 1.363). A.G. Mikos from Rice University in the USA had the highest *j* of 44. Mikos had only 44 highly cited corresponding-author articles in the Web of Science category of biomedical engineering. Prof. Mikos is a member of the National Academy of Engineering, the National Academy of Medicine, the National Academy of Inventors, and the Academy of Athens (Sikavitsas, 2020). He won awards including the Lifetime Achievement Award of the Tissue Engineering and Regenerative Medicine International Society-Americas, the Founders Award of the Society for Biomaterials, the Robert A. Pritzker Distinguished Lec turer Award of the Biomedical Engineering Society, and the Marshall R. Urist Award for Excellence in Tissue Regeneration Research of the

Orthopedic Research Society (Sikavitsas, 2020). Followed by D.L. Kaplan who published only 58 highly cited articles, including 41 corresponding-author articles with Y-index = (41, $\pi/2$).

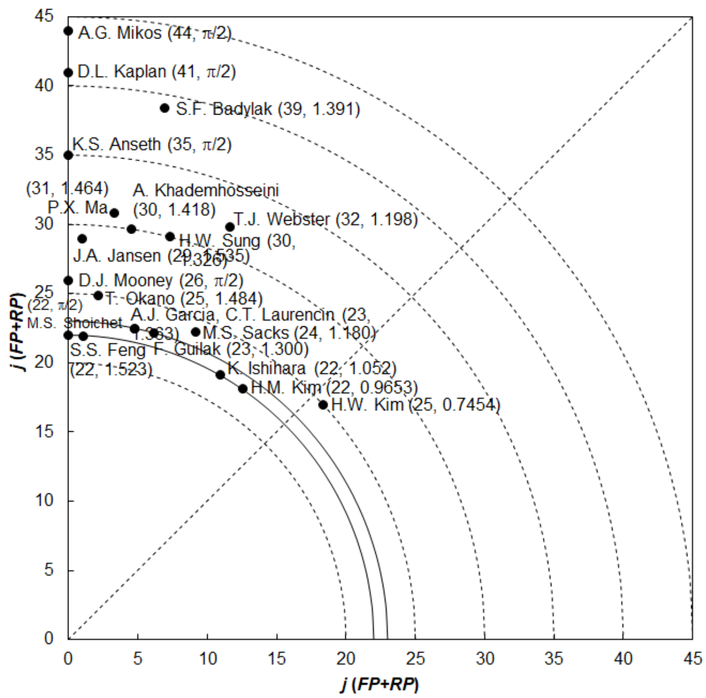

Fig. 2. Distribution of the top 20 highly cited authors with their Y-index values ($j \geq 22$)

M.S. Shoichet (22, $\pi/2$), S.S. Feng (22, 1.523), K. Ishihara (22, 1.052), and H.M. Kim (22, 0.9653) had the same value for j of 22. These authors are located on the same curve (j = 22) in Fig. 2, indicating that they have the same publication potential with different publication characteristics (Ho and Hartley, 2016). Shoichet ($h = \pi/2$) had only corresponding-author articles. Feng (h = 1.523) had a higher ratio of corresponding-author articles to first-author articles, than Ishihara (h = 1.052) and Kim (h = 0.9653). T. Okano (25, 1.484) and H.W. Kim (25, 0.7454) also had the same publication potential with a j of 25. Okano (h = 1.484) had more corresponding-author articles but Kim (h = 0.7454) had more first-author articles. Similarly, A. Khademhosseini (30, 1.418) and H.W. Sung (30, 1.326) as well as A.J. Garcia (23, 1.363), C.T. Laurencin (23, 1.363), and F. Guilak (23, 1.3) are located on the same curves j = 30 and j = 23, respectively.

The h of A.G. Mikos, D.L. Kaplan, K.S. Anseth, D.J. Mooney, and M.S. Shoichet were all the same of $\pi/2$ and located on the same straight line (y-axis) in Fig. 2. All these authors had the same publication characteristics with only the corresponding-author articles (Giannoudis et al., 2021). Mikos had the greatest publication potential with a j of 44 than Kaplan, Anseth, Mooney, and Shoichet with a j of 41, 35, 26, and 22, respectively. Among the top 27 authors, H.W. Kim (25, 0.7454) was the only one who published more first-author articles than corresponding-author articles. In addition, C.T. Wu (18, 0.2783) published the most first-author highly cited articles in the Web of Science category of biomedical engineering.

3.5. The Most Frequently Cited Articles

The most frequently cited articles with TC_{year} as a citation indicator show their impact on a research topic. Citation indicator C_{year} was proposed to evaluate the most impactful articles in the most recent year (Ho, 2012; 2021). Figure 3 shows the citation history of the top 10 most frequently cited articles. Article by Kokubo and Takadama (2006) not only ranked top with TC_{2020} of 5,260 but also ranked top in C_{year} from 2009 to 2018 the Web of Science category of biomedical engineering. Article by Maes et al. (1997) ranked 7th with TC_{2020} of 3,139 and ranked top in C_{year} from 2000 to 2008 but ranked 102nd in the most the recent year of 2020 with C_{2020} of 90. It has been found that highly cited publications might not be always in high-impact positions (Ho and Kahn, 2014). Furthermore, highly cited publications might not be the most impactful in the most recent year (Ho, 2021). Some recent publications, which did not get enough time to accumulate numbers of citations, would be omitted if only TC_{year} was used for evaluation (Fu and Ho, 2015), for example, an article published in 2017 by Litjens et al. (2017) ranked 11st with TC_{2020} of 2,452 but ranked top in C_{year} in 2019 and 2020.

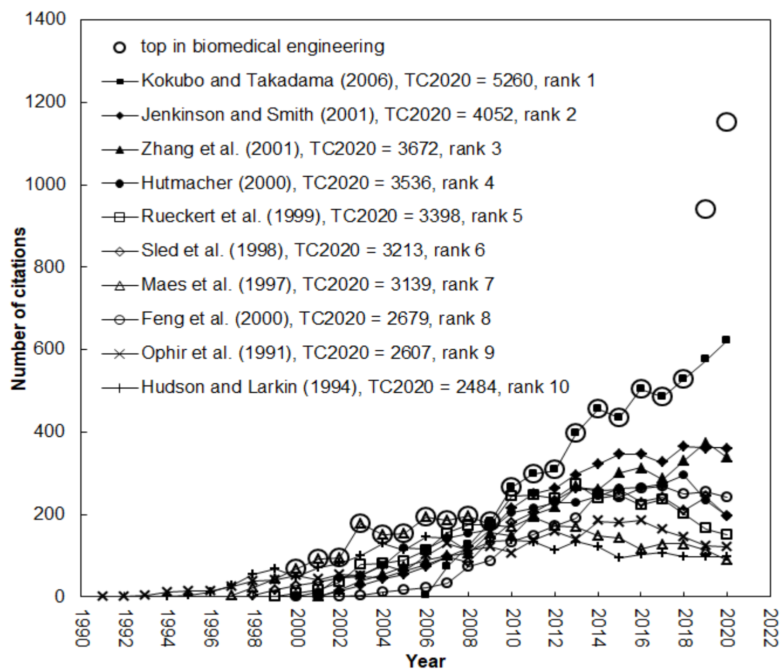

Fig. 3. Citation histories of the top 10 most frequently cited articles in the Web of Science category of biomedical engineering.

The article had a high citation in 2020 shows the related research is popular in the Web of Science category of biomedical engineering in recent years. Similarly, articles entitled "Efficient multi-scale 3D CNN with fully connected CRF for accurate brain lesion segmentation" (Kamnitsas et al., 2017) by Kamnitsas et al. and "Brain tumor segmentation with Deep Neural Networks" (Havaei et al., 2017) by Havaei et al. had a C_{2020} of 356 (ranked 6th) and a C_{2020} of 310 (ranked 9th) and a TC_{2020} of 943 (ranked 84th) and a TC_{2020} of 891 (ranked 94th), respectively. Only using the TC_{year} was not enough to identify some excellent articles in the most recent years (Fu and Ho, 2015). Table 5 presents the top 10 most frequently cited articles in the Web of Science category of biomedical engineering. Only the top three highly cited articles were also ranked top ten in C_{2020} as the most impactful in 2020, including the article entitled "How useful is SBF in predicting in vivo bone bioactivity" (Kokubo and Takadama, 2006) by Kokubo and Takadama at Chubu University in Japan with a TC_{2020} of 5,260 (ranked 1st) and a C_{2020} of 623 (ranked 2nd); "A global optimisation method for robust affine registration of brain images" (Jenkinson and Smith, 2001) by Jenkinson and Smith at the University of Oxford in the UK with a TC_{2020} of 4,052 (ranked 2nd) and a C_{2020} of 361 (ranked 5th); and "Segmentation of brain MR images through a hidden Markov random field model and the expectation-maximization algorithm" (Zhang et al., 2001) the University of Oxford in the UK with a TC_{2020} of 3,672 (ranked 3rd) and a C_{2020} of 339 (ranked 7th).

Table 5
The top 10 most impactful articles in 2020 in the Web of Science category of biomedical engineering

Rank (TC_{2020})	Rank (C_{2020})	Article title	Country	Reference
1 (5,260)	2 (623)	How useful is SBF in predicting in vivo bone bioactivity	Japan	Kokubo and Takadama (2006)
2 (4,052)	5 (361)	A global optimisation method for robust affine registration of brain images	UK	Jenkinson and Smith (2001)
3 (3,672)	7 (339)	Segmentation of brain MR images through a hidden Markov random field model and the expectation-maximization algorithm	UK	Zhang et al. (2001)
4 (3,536)	24 (196)	Scaffolds in tissue engineering bone and cartilage	Singapore	Hutmacher (2000)
5 (3,398)	38 (151)	Nonrigid registration using free-form deformations: Application to breast MR images	UK	Rueckert et al. (1999)
6 (3,213)	24 (196)	A nonparametric method for automatic correction of intensity nonuniformity in MRI data	Canada	Sled et al. (1998)
7 (3,139)	102 (90)	Multimodality image registration by maximization of mutual information	Belgium	Maes et al. (1997)
8 (2,679)	16 (242)	A mechanistic study of the antibacterial effect of silver ions on Escherichia coli and Staphylococcus aureus	China, South Korea	Feng et al. (2000)
9 (2,607)	60 (121)	Elastography: A quantitative method for imaging the elasticity of biological tissues	USA	Ophir et al. (1991)
10 (2,484)	87 (97)	Accelerated image-reconstruction using ordered subsets of projection data	Australia	Hudson and Larkin (1994)

TC_{2020}: total citations from Web of Science Core Collection since publication year to the end of 2020; C_{2020}: citations in 2020 only.

3.6. Words in Article Title, Author Keywords, and KeyWords Plus

Analysis of used words in article title, author keywords, and *KeyWords Plus* were proposed for the main research topics (Li et al., 2009). In the Web of Science category of biomedical engineering, 8,736 (82% of 10,674 highly cited articles) and 10,224 (96%) highly cited articles contained author keywords and *KeyWords Plus* information in SCI-EXPANDED, respectively. Table 6 shows the top 20 most used words in highly cited article titles, author keywords, and *KeyWords Plus* in biomedical engineering. Tissue engineering was found to be the most frequently used author keyword (in 528 articles; 6.0% of total 8,736 highly cited articles with author keyword information in SCI-EXPANDED) followed by hydroxyapatite (345; 3.9%). The most frequently cited article related to tissue engineering was "Scaffolds in tissue engineering bone and cartilage" (Hutmacher, 2000) with a TC_{2020} of 3,536 (ranked 4th) and a C_{2020} of 196 (ranked 24th). Bone was the most frequently used keyword in article title (in 872 articles; 8.2% of total 10,674 highly cited articles in the Web of Science category of biomedical engineering) followed by tissue (863; 8.1%). The article entitled "How useful is SBF in predicting in vivo bone bioactivity" (Kokubo and Takadama, 2006) was the most cited article related to the bone with a TC_{2020} of 5,260 (ranked 1st) and a C_{2020} of 623 (ranked 2nd). The most appeared *KeyWords Plus* was in-vitro (in 1,043 articles; 10% of total 10,224 highly cited articles with *KeyWords Plus* information in SCI-EXPANDED) followed by cells (518; 5.1%), tissue (513; 5.0%), and model (498; 4.9%).

Table 6
Top 20 most used words in highly cited article title, author keywords, and *KeyWords Plus*

Words in title	TP	R (%)	Author keywords	TP	R (%)	KeyWords Plus	TP	R (%)
bone	872	1 (8.2)	tissue engineering	528	1 (6.0)	in-vitro	1,043	1 (10)
tissue	863	2 (8.1)	hydroxyapatite	345	2 (3.9)	cells	518	2 (5.1)
human	719	3 (6.7)	scaffold	286	3 (3.3)	tissue	513	3 (5.0)
cells	645	4 (6.0)	hydrogel	264	4 (3.0)	model	498	4 (4.9)
cell	594	5 (5.6)	drug delivery	256	5 (2.9)	bone	471	5 (4.6)
scaffolds	558	6 (5.2)	biocompatibility	245	6 (2.8)	growth	432	6 (4.2)
engineering	554	7 (5.2)	chitosan	221	7 (2.5)	mechanical-properties	415	7 (4.1)
properties	510	8 (4.8)	collagen	210	8 (2.4)	differentiation	408	8 (4.0)
vitro	470	9 (4.4)	mechanical properties	198	9 (2.3)	behavior	401	9 (3.9)
poly	446	10 (4.2)	titanium	170	10 (1.9)	in-vivo	387	10 (3.8)
surface	427	11 (4.0)	electrospinning	166	11 (1.9)	adhesion	344	11 (3.4)
analysis	426	12 (4.0)	cell adhesion	154	12 (1.8)	delivery	315	12 (3.1)
nanoparticles	423	13 (4.0)	bone	146	13 (1.7)	expression	315	12 (3.1)
delivery	414	14 (3.9)	biomechanics	145	14 (1.7)	scaffolds	310	14 (3.0)
effect	408	15 (3.8)	bone tissue engineering	143	15 (1.6)	biomaterials	306	15 (3.0)
vivo	389	16 (3.6)	osteoblast	142	16 (1.6)	system	302	16 (3.0)
stem	374	17 (3.5)	surface modification	138	17 (1.6)	proliferation	290	17 (2.8)
model	369	18 (3.5)	cytotoxicity	117	18 (1.3)	implants	286	18 (2.8)
hydroxyapatite	358	19 (3.4)	nanoparticle	115	19 (1.3)	design	282	19 (2.8)
mechanical	338	20 (3.2)	nanoparticles	103	20 (1.2)	collagen	279	20 (2.7)

TP: total highly cited articles; *R*: rank

4. Conclusions

In the past three decades, 11,905 highly cited documents out of nine document types have been published in the Web of Science category of biomedical engineering in SCI-EXPANDED. Authors from 75 countries have published 10,674 highly cited articles in 95 journals, of which only 66 journals are included in the Web of Science category of biomedical engineering in 2020. The most highly cited articles were found in 2010. The *Biomaterials* published the most articles followed distantly by other journals. Highly cited articles were published not only in high-impact factor journals but also in lower impact factor journals. The United States dominated the seven publication indicators, while the United Kingdom has the highest number of citations per publication. The Harvard University in the USA had not only the ascendancy of production but also the most-frequent partners. From *Y*-index analysis results, A.G. Mikos of Rice University in the United States was the author with the most potential for publication. Articles by Kokubo and Takadama (2006), Jenkinson and Smith (2001), and Zhang et al. (2001) were included in the top ten most cited and also included in the top ten most influential in 2020. Articles about tissue engineering had higher contributions in the Web of Science category of biomedical engineering.

References

Apostolopoulos, I.D. and Mpesiana, T.A. (2020), Covid-19: Automatic detection from X-ray images utilizing transfer learning with convolutional neural networks. Physical and Engineering Sciences in Medicine, 43 (2), 635-640.

Brewer, C.R., Brown, J.H.U., Hellman, L.P., Pahl, H.B. and Tuve, T.W. (1962). Ideas or Instruments—the Development of Biomedical Engineering. Academic Medicine, 37(12), 1285-1290.

Chiu, W.T. and Ho, Y.S. (2005), Bibliometric analysis of homeopathy research during the period of 1991 to 2003. Scientometrics, 63 (1), 3-23.

Chuang, K.Y., Wang, M.H. and Ho, Y.S. (2011), High-impact papers presented in the subject category of water resources in the Essential Science Indicators database of the Institute for Scientific Information. Scientometrics, 87 (3), 551-562.

Donahue, J. and Sonnenburg, D.E. (1974), Clinical engineering: Now and in future. Medical Progress Through Technology, 2 (3), 127-132.

Feng, Q.L., Wu, J., Chen, G.Q., Cui, F.Z., Kim, T.N. and Kim, J.O. (2000), A mechanistic study of the antibacterial effect of silver ions on Escherichia coli and Staphylococcus aureus. Journal of Biomedical Materials Research, 52 (4), 662-668.

Fu, H.Z. and Ho, Y.S. (2015), Top cited articles in thermodynamic research. Journal of Engineering Thermophysics, 24 (1), 68-85.

Fu, H.Z., Wang, M.H. and Ho, Y.S. (2012), The most frequently cited adsorption research articles in the Science Citation Index (Expanded). Journal of Colloid and Interface Science, 379 (1), 148-156.

Garfield, E. (1987), Exploring the frontiers of biomedical engineering: An overview of historical and current considerations. Current Contents, 10, 3-11.

Giannoudis, P.V., Chloros, G.D. and Ho, Y.S. (2021), A historical review and bibliometric analysis of research on fracture nonunion in the last three decades. International Orthopaedics, 45, 1663-1676.

Havaei, M., Davy, A., Warde-Farley, D., Biard, A., Courville, A., Bengio, Y., Pal, C., Jodoin, P.M. and Larochelle, H. (2017), Brain tumor segmentation with Deep Neural Networks. Medical Image Analysis, 35, 18-31.

Ho, Y.S. (2012), Top-cited articles in chemical engineering in Science Citation Index Expanded: A bibliometric analysis. Chinese Journal of Chemical Engineering, 20 (3), 478-488.

Ho, Y.S. (2013), The top-cited research works in the Science Citation Index Expanded. Scientometrics, 94 (3), 1297-1312.

Ho, Y.S. (2014), A bibliometric analysis of highly cited articles in materials science. Current Science, 107 (9), 1565-1572.

Ho, Y.S. (2019), Bibliometric analysis of the Journal of Orthopaedic Research from 1991 to 2018. Orthopedic Research Online Journal, 6 (2), 574-584.

Ho, Y.S. (2021), A bibliometric analysis of highly cited publications in Web of Science category of emergency medicine. Signa Vitae, 17 (1), 11-19.

Ho, Y.S. and Hartley, J. (2016), Classic articles published by American scientists (1900-2014): A bibliometric analysis. Current Science, 111 (7), 1156-1165.

Ho, Y.S. and Kahn, M. (2014), A bibliometric study of highly cited reviews in the Science Citation Index Expanded™. Journal of the Association for Information Science and Technology, 65 (2), 372-385.

Ho, Y.S., Satoh, H. and Lin, S.Y. (2010), Japanese lung cancer research trends and performance in Science Citation Index. Internal Medicine, 49 (20), 2219-2228.

Hsu, Y.H.E. and Ho, Y.S. (2014), Highly cited articles in health care sciences and services field in Science Citation Index Expanded: A bibliometric analysis for 1958-2012. Methods of Information in Medicine, 53 (6), 446-458.

Hsu, Y.H.E., Yang, Y.T., Wang M.H. and Ho, Y.S. (2020), Bibliometric analysis of highly cited publications in health policy and services. COLLNET Journal of Scientometrics and Information Management, 14 (1), 177-202.

Hudson, H.M. and Larkin, R.S. (1994), Accelerated image-reconstruction using ordered subsets of projection data. IEEE Transactions on Medical Imaging, 13 (4), 601-609.

Hutmacher, D.W. (2000), Scaffolds in tissue engineering bone and cartilage. Biomaterials, 21 (24), 2529-2543.

Jasper, H. (1949), Diffuse projection systems: The integrative action of the thalamic reticular system. Electroencephalography and Clinical Neurophysiology, 1 (4), 405-420.

Jenkinson, M. and Smith, S. (2001), A global optimisation method for robust affine registration of brain images. Medical Image Analysis, 5 (2), 143-156.

Juang, G.D., Lin, S.M. and Ho, Y.S. (2021), Highly cited publications in the Web of Science category of anesthesiology in the Science Citation Index Expanded: A bibliometric analysis. Journal of Scientometric Research, 10 (2), 251-258.

Kamnitsas, K., Ledig, C., Newcombe, V.F.J., Sirnpson, J.P., Kane, A.D., Menon, D.K., Rueckert, D. and Glocker, B. (2017), Efficient multi-scale 3D CNN with fully connected CRF for accurate brain lesion segmentation. Medical Image Analysis, 36, 61-78.

Kokubo, T. and Takadama, H. (2006), How useful is SBF in predicting in vivo bone bioactivity? Biomaterials, 27 (15), 2907-2915.

Li, L.L., Ding, G.H., Feng, N., Wang, M.H. and Ho, Y.S. (2009), Global stem cell research trend: Bibliometric analysis as a tool for mapping of trends from 1991 to 2006. Scientometrics, 80 (1), 39-58.

Li, Z. and Ho, Y.S. (2008), Use of citation per publication as an indicator to evaluate contingent valuation research. Scientometrics, 75 (1), 97-110.

Litjens, G., Kooi, T., Bejnordi, B.E., Setio, A.A.A., Ciompi, F., Ghafoorian, M., van der Laak, J.A.W.M., van Ginneken, B. and Sánchez, C.I. (2017), A survey on deep learning in medical image analysis. Medical Image Analysis, 42, 60-88.

Long, X., Huang, J.Z. and Ho, Y.S. (2014), A historical review of classic articles in surgery field. American Journal of Surgery, 208 (5), 841-849.

Maes, F., Collignon, A., Vandermeulen, D., Marchal, G. and Suetens, P. (1997), Multimodality image registration by maximization of mutual information. IEEE Transactions on Medical Imaging, 16 (2), 187-198.

Monge-Nájera, J. and Ho, Y.S. (2017), El Salvador publications in the Science Citation Index Expanded: subjects, authorship, collaboration and citation patterns. Revista de Biología Tropical, 65 (4), 1428-1436.

Moruzzi, G. and Magoun, H.W. (1949), Brain stem reticular formation and activation of the EEG. Electroencephalography and Clinical Neurophysiology, 1 (4), 455-473.

Oakes, J.B. and Johns, R.J. (1973), The role of clinical engineering in health-care delivery. IEEE Transactions on Biomedical Engineering, 20 (3), 225-227.

Ophir, J., Céspedes, I., Ponnekanti, H., Yazdi, Y. and Li, X. (1991), Elastography: A quantitative method for imaging the elasticity of biological tissues. Ultrasonic Imaging, 13 (2), 111-134.

Patterson, R.P. (2003), Otto Schmitt: A father of biomedical engineering and master gadgeteer. Proceedings of the 25th Annual International Conference of the IEEE Engineering in Medicine and Biology Society, 25 (1-4), 3461-3463.

Rueckert, D., Sonoda, L.I., Hayes, C., Hill, D.L.G., Leach, M.O. and Hawkes, D.J. (1999), Nonrigid registration using free-form deformations: Application to breast MR images. IEEE Transactions on Medical Imaging, 18 (8), 712-721.

Shin, H.C., Roth, H.R., Gao, M.C., Lu, L., Xu, Z.Y., Nogues, I., Yao, J.H., Mollura, D. and Summers, R.M. (2016), Deep convolutional neural networks for computer-aided detection: CNN architectures, dataset characteristics and transfer learning. IEEE Transactions on Medical Imaging, 35 (5), 1285-1298.

Sikavitsas, V.I. (2020), Introduction to editorial board member: Professor Antonios (Tony) G. Mikos. Bioengineering & Translational Medicine, 5 (1), e10155.

Sled, J.G., Zijdenbos, A.P. and Evans, A.C. (1998), A nonparametric method for automatic correction of intensity nonuniformity in MRI data. IEEE Transactions on Medical Imaging, 17 (1), 87-97.

Usman, M. and Ho, Y.S. (2020), A bibliometric study of the Fenton oxidation for soil and water remediation. Journal of Environmental Management, 270, Article Number 110886.

Wang, M.H., Fu, H.Z. and Ho, Y.S. (2011), Comparison of universities' scientific performance using bibliometric indicators. Malaysian Journal of Library & Information Science, 16 (2), 1-19.

Yeung, A.W.K. and Ho, Y.S. (2019), Highly cited dental articles and their authors: An evaluation of publication and citation characteristics. Journal of Investigative and Clinical Dentistry, 10 (4), Article Number: e12462.

Zhang, Y.Y., Brady, M. and Smith, S. (2001), Segmentation of brain MR images through a hidden Markov random field model and the expectation-maximization algorithm. IEEE Transactions on Medical Imaging, 20 (1), 45-57.