International publication trends in Biomedical Signal Processing research: A bibliometric analysis (2009-2018)

Yanbin Cui
Changzhi Medical College
Ping Zhang
Army Medical University
Yan Kang
Northeastern University
Liang Zhou (13983081938@163.com)
Army Medical University https://orcid.org/0000-0001-8384-3828

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Abstract

Background This study aimed to analyze and assess the scientific outputs of biomedical signal processing by using bibliometric analysis.Methods Data were obtained from the WoSCC of Thomson Reuters, on January 21, 2019. VOSviewer (Leiden University, Van Eck and Waltman, Netherlands) and carrot 2 (Poznan University of Technology, Dawid Weiss, Poland) were used to analyze the knowledge maps and clusters of countries, research area and hot topics.Results A total of 335 articles on biomedical signal processing were identified. The number of publications increased only mildly during from 2009 (n=14) to 2018 (n=62). The majority of articles were published in the USA, and the leading institute was University of California System. Van Huffel S was the top authors on the topic, and the research area of “Engineering” generated the most publications. Cluter analysis (keywords and terms) indicated that “algorithm” and “extracted features” was the most hot topics on biomedical signal processing.Conclusion Overall, Through analysis of biosignal single processing related research in the past 10 years, the results found that the close international cooperation in this field, and the future research trends may be the signal acquisition methods and signal processing algorithms. They can provide reference for researchers in related field to choose research directions and find cooperative resources.

Background

Biomedical signal processing is an important research field in biomedical engineering, witch has significance research value in the fields of life science, clinical diagnosis, disease prevention and medical instrument production. Because of biomedical signals originate from human life activities, there are diversity and complexity in processing. As a result, this field has become the interdisciplinary category of many subjects and technologies, which includes clinical medicine, biology, pattern recognition, machine learning, signal modeling and simulation[1-6] .

Bibliometric analysis is a branch of library and information science that uses mathematical statistics to quantitatively describe, evaluate and predict academic status and development trends[7-8]. It has significant objective, quantitative and modeled macro research advantages[8]. At present, there are many professional softwares that can be used for bibliometric analysis[9]. In this study, VOSviewer was selected for visual analysis of bibliometrics, which can convert the large amount of literature data into a bibliometric map[10]. The researchers can understand the knowledge structure more directly, and find the hot topics and research areas from the maps. Biomedical signal processing have published a substantial amount of original research based on care digital signal processing, electrocardiosignal, and brain-computer interface, etc[11-13]. However, there are no bibliometric analyses that have explored research related to biomedical signal processing. This study used CitespaceIII to analyze biomedical signal processing articles retrieved on the Web of Science (Thomson Reuters Company) database and provides a retrospective and current view of the mainstream research on biomedical signal processing throughout the world.

Methods

All the data for this study were obtained from the Web of Science Core Collection (WoSCC) of Thomson Reuters, on January 21, 2019. The WoSCC, which includes the Social Sciences Citation Index, Current Chemical Reactions, and Index Chemicus, is the most frequently used source of scientific information. The search term “biomedical signal processing” was used to retrieve titles, keywords, author information, abstracts, and references published from 2009 to 2018. The following search string was used: TS= (“biomedical signal processing”) AND document type:(ARTICLE OR REVIEW). Data were downloaded from WoS in “Full record and cited references” and “Comma Separated Values (CSV)” formats.

The information statistics of this study mainly include authors, research institutions, countries and research fields, and the indicators were publication and citation. Microsoft Excel 2016 (Microsoft, Redmond, WA, USA) software tools were used to analyze the data[14]. VOSviewer 1.6.9 and carrot2 were used to analyze publication outputs and construct knowledge maps, to visualize the networks and clusters for countries, keywords and terms in biomedical signal processing[10, 15].

Results

Overall publication trends

A total of 335 studies on biomedical signal processing, published from 2009 to 2018, were retrieved from the WoSCC (Figure 1). Although the number of publications increased only mildly during from 2008 (n=14) to 2017 (n=62), the number of citation increased substantially from 2008 (n=5) to 2016 (n=1,081) (Figure 1). 269 studies (80.03%) were cited at least once, with an average of 13.08 citations per article for 4,381 total citations. We calculated the linear regression and found y=4.77x-7.27 with r^2=0.884 (publication); y=125.66x-258.60 with r^2=0.954(citation), respectively (Figure 2).

The most-cited articles

Among the 335 articles, the three most-cited articles were: “Surface EMG based muscle fatigue evaluation in biomechanics” by Mario Cifrek published in 2009 in *Clinical biomechanics* (196 citations, 17.82 citations per year)[16], “Zero-Velocity Detection-An Algorithm Evaluation” by Skog published in 2010 in *IEEE Transactions on Biomedical Engineering* (177 citations, 17.70 citations per year)[17], “Source Separation From Single-Channel Recordings by Combining Empirical-Mode Decomposition and Independent Component Analysis” by Mijović published in 2010 in *IEEE Transactions on Biomedical Engineering* (151 citations, 15.10 citations per year)[18]; See the Table 1 for the following 7 most-cited articles[19-25].

Countries or regions

These research studies were published by 49 countries or regions. The top 10 countries published 266 of the 335 studies, accounting for 79.40% of the total number of publications, which were cited 2,886 times. The country with the greatest number of publications was the USA (n=71), followed by Italy (n=31) and England (n=24); the country with the greatest number of citations was the USA (1,041 citations), Italy

(341 citations) and Germany (272 citations); the country with the greatest per number of citations was USA (n=14.66 citations per article), Germany (12.95 citations per article) and Turkey (11.44 citations per article) (Table 2).

Countries or regions used in the 335 papers were analyzed by VOSviewer. The 57 countries or regions (defined as being used more than 5 times within documents in all of articles) were classified to 5 clusters (Figure 3):

1. Cluster 1–Austrilia (n=20), Belgium (n=15), Canada (n=20), Netherlands (n=10), People's R China (n=21), Slovenia (n=5), South Korea (n=9), the USA (n=71);

2. Cluster 2–Austria (n=6), India (n=21), Romania (n=5), Singapore (n=7), Turkey (n=16);

3. Cluster 3–England (n=23), Finland (n=7), Germany (n=20), Poland (n=9), Taiwan (n=7);

4. Cluster 4–France (n=13), Italy (n=31), Switzerland (n=5);

5. Cluster 5–Brazil (n=7), Colombia (n=5), Spain (n=21).

Institutions and Authors

Among the 80 institutions, the top 10 institutions published 67 literatures, accounting for 20.00% of the total number of publications, which were cited 780 times. University of California System was the most publications (n=10), followed by the International Medical Equipment Collaborative (n=7) and KU Leuven (n=7), et al; In addition, the total number of authors retrieved in the 335 articles was 1,184, an average of 3.53 authors per article. The top ten authors accounted for 38 studies, 11.34% of the total, which were cited 685 times. Van Huffel S (n=6) was the most publications' author, followed by Casciaro S (n=4) and Conversano F(n=4), et al (Table 3).

Research area analysis

These research studies were published by 52 research areas. The top 10 areas published 303 of the 335 studies, accounting for 90.45% of the total number of publications, which were cited 4,055 times. The top 3 number of publications were Engineering biomedical (n=149), Engineeeing electrical electronic (n=100) and Computer science interdisciplinary applications (n=46); the top 3 number of citations were Engineering biomedical (2,042 citations), Engineeeing electrical electronic (1,272 citations) and Computer science interdisciplinary applications (533 citations); The top 3 per number of citations were Mathematical computatonal biology (15.30 per article), Instruments instrumentation (14.63 per article) and Physiology (14.55 per article) (Table 4).

Hot hotspots

There were 335 papers on biomedical signal processing research had been included in this analysis. The visualization was generated by the Carrot2 system based on the 19 clusters. The top 5 clusters were

Extracted features (n=53), Classification accuracy(n=37), Electrocardiogram ECG(n=36), Proposed model(n=34), Proposed design(n=31) (Figure 4).

In Figure 5, the left hand is the network of keywords, and the right hand is the network of keywords plus. In this study, keyword plus clustering results were used as the research direction of hot topics. Therefore, there are 1,114 keywords had been used to analyze by VOSviewer. The 53 keywords (defined as being used more than 5 times within documents in all of articles) were classified to 4 clusters:

I. Cluster 1(model and algorithm)–algorithm (n=31), frequency (n=8), model (n=11), neural-network (n=5), optimization (n=5), et al;

II. Cluster 2 (physiological signal recording)–brain (n=7), EEG (n=14), electrocadigram (n=9), recordings (n=12), signals (n=7), et al;

III. Cluster 3 (Signal transform and analysis)–decomposition (n=8), design (n=6), entropy (n=5), power (n=5), transform (n=15), et al;

IV. Cluster 4 (diagnosis of clinical diseases)–diagnosis (n=6), features (n=9), parkinsons-disease (n=5), reconstruction (n=13), validation (n=7), et al.

Discussion

A bibliometric analysis of biomedical signal processing research publications from WoSCC during the year 2009–2018 has been conducted. The analysis included three aspects: publication and citation trends, distribution of scientific research forces, research hotspots. Some findings were as follows:

Publication and citation trends

Biomedical signal processing research publication trends show that the publication of biomedical signal processing related articles increased slowly in the past decade, but its citation increased rapidly. This interest may be due to the number of basic research in this field is relatively small, but its application field is relatively wide, especially the interdisciplinary subject like biomedical signal processing.

From the 10 most-cited articles, their main research direction comes from the algorithm and mathematical model of biological signal processing. The most-cited is the research from Cifrek M, which summarized the signal methods and techniques from the standpiont of applicability to sEMG signals in fatigue-inducing situations relevant to the broad field biomechanics[16]; and this review as a basic konwleage had been mainly cited in research area of sports science, engineering biomedical and neurosciences, et al[26-28].

Distribution of scientific research forces

The USA published the most research on biomedical signal processing; this phenomenon is the same as many other research fields. This shows that the United States is a leader in the field. However, it is worth

noting that German, Turkish and Italian research publications are small, but the average citation is high. In addition, although Peoples R China has the same publication as Germany, its quotation is the lowest in Top10, which indicates that the quality of academic papers in this field needs to be further improved.

From the perspective of national collaborative networks, the most connected clusters are between the United States and Canada.Other countries (regions) under the same cluster also include Austrilia, Belgium, Netherlands, People's R China, Slovenia, and South Korea, which are also the largest cluster in the collaboration network, indicating the frequent exchange of international scientific research cooperation among these countries (regions).

Research hotspots

The research hotspots mainly come from the clustering analysis of the subject words and key words included in the literature.

From the clustering analysis of subject words, the main research contents of these 5 clusters are as follows:

1) Extracted features: By extracting the features of human physiological signals, a feasible discriminant, diagnostic or classification model is established to accurately recognize the physiological state of the disease[29-31].

2) Classification accuracy: Through optimization algorithm, the accuracy of signal recognition model can be improved, including time series, wavelet analysis and machine learning[31-33].

3) Electrocardiogram ECG: Because of ECG is highly correlated with the diagnosis of many diseases, it has become an important part of the field of biomedical signal processing; research directions include signal monitoring, model algorithm optimization, disease screening, etc[34-36].

4) Proposed model: According to the data characteristics of biological signals, an algorithm model for signal recognition is constructed[37-38].

5) Proposed design: According to the requirement of biological signal acquisition, the hardwares and equipments were designed and improved[39-41].

From the clustering analysis of keywords, the main research contents of these 4 clusters are as follows:

1) Cluster 1 (model and algorithm): Establishment and optimization of mathematical models in the process of biological signal processing, including signal extraction, recognition and classification, and data conversion, etc[27, 29-30].

2) Cluster 2 (physiological signal recording): Signal acquisition and recording, including the design of signal acquisition hardware, the selection of recording methods and the determination of signal types, etc[39, 42-43].

3) Cluster 3 (Signal transform and analysis):Conversion of special signals or variables, such as signal processing of image data[32, 44-45].

4) Cluster 4 (diagnosis of clinical diseases): Based on the recognition and classification of signals, the diagnosis model of clinical diseases is established, which is mainly composed of ECG, EEG and image signals[46-48].

Conclusions

Overall, Through analysis of biomedical signal processing related research in the past 10 years, which can provide reference for researchers in related field to choose research directions and find cooperative resources. Major findings: (i) biomedical signal processing is an important link between biomedical engineering and clinical diagnostics; technological advances in this field may directly affect the diagnostic ability of future clinical diseases. (ii) International cooperation in this field is frequent, and scientific research is mainly distributed in North America and Europe. (iii) Signal acquisition methods and signal processing algorithms may be an important direction of future development, which deserves the attention of relevant professional researchers.

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Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data and material

The datasets used and analyzed during the current study are available from the corresponding author upon reasonable requests.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

LZ leaded the method application, experiment conduction and the result analysis. YC and PZ participated in the design of the research and the revision of the manuscript. KY provided theoretical guidance, the key term extraction program development and the revision of this paper. All authors read and approved the final manuscript.

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Not applicable.

Tables

Table 1. Top 10 most-cited articles on biomedical signal processing

Article	Journal	Year of publication	No. of aunnal year citations	No. of citations
Surface EMG based muscle fatigue evaluation in biomechanics[16]	Clinical biomechanics	2009	196	17.82
Zero-Velocity Detection-An Algorithm Evaluation[17]	IEEE Transactions on Biomedical Engineering	2010	177	17.70
Source Separation From Single-Channel Recordings by Combining Empirical-Mode Decomposition and Independent Component Analysis[18]	IEEE Transactions on Biomedical Engineering	2010	151	15.10
Scalable tensor factorizations for incomplete data[19]	IEEE Transactions on Image Processing	2011	147	16.33
Improved complete ensemble EMD: A suitable tool for biomedical signal processing[20]	Biomedical Signal Processing and Control	2014	142	23.67
Introduction to multifractal detrended fluctuation analysis in Matlab[21]	Frontiers in Physiology	2012	135	16.88
Deep learning in bioinformatics[22]	Briefings in Bioinformatics	2016	81	27.00
Deep Convolutional Neural Network for Inverse Problems in Imaging[23]	IEEE Transactions on Signal Processing	2017	74	24.67
Automatic Detection of Swallowing Events by Acoustical Means for Applications of Monitoring of Ingestive Behavior[24]	IEEE Transactions on Biomedical Engineering	2010	73	7.30
Variational Bayesian Inference for a Nonlinear Forward Model[25]	IEEE Transactions on Image Processing	2009	73	6.64

Table 2. Top 10 countries or regions on biomedical signal processing

Rank	Countries or regions	No. of articles	No. of citations	Citations per article
1	USA	71 (21.19%)	1,041 (23.76%)	14.66
2	Italy	31 (9.25%)	341 (7.78%)	11.00
3	England	24 (7.16%)	250 (5.71%)	10.42
4	Germany	21 (6.27%)	272(6.21%)	12.95
5	India	21 (6.27%)	214 (4.88%)	10.19
6	Peoples R China	21 (6.27%)	77 (1.76%)	3.62
7	Spain	21 (6.27%)	179 (4.09%)	8.52
8	Australia	20 (5.97%)	177 (4.04%)	8.85
9	Canada	20 (5.97%)	152 (3.47%)	7.60
10	Turkey	16 (4.78%)	183 (4.18%)	11.44

Table 3. Top 10 authors and institution on biomedical signal processing

Rank	Institution	No. of articles	Rank	Author	No. of articles
1	University of California System	10 (2.99%)	1	Van Huffel S	6 (1.80%)
2	International Medical Equipment Collaborative	7 (2.10%)	2	Casciaro S	4 (1.20%)
3	KU Leuven	7 (2.10%)	3	Conversano F	4 (1.20%)
4	University of London	7 (2.10%)	4	Markovic D	4 (1.20%)
5	Centre National De La Rec-herche Scientifique	6 (1.80%)	5	Melia U	4 (1.20%)
6	Ciber Centro De Investigaion Biomedica En Red	6 (1.80%)	6	Vallverdu M	4 (1.20%)
7	Biomedical Research Networking Centres	6 (1.80%)	7	Caminal P	3 (0.90%)
8	Universite Paris Saclay	6 (1.80%)	8	Charlton PH	3 (0.90%)
9	University of Bologna	6 (1.80%)	9	Chen X	3 (0.90%)
10	University of Oxford	6 (1.80%)	10	Cifrek M	3 (0.90%)

Table 4. Top 10 research areas on biomedical signal processing

Rank	Research area	No. of articles	No. of citations	Citations per article
1	Engineering biomedical	149 (44.48%)	2,042 (46.61%)	13.70
2	Engineeeing electrical electronic	100 (29.85%)	1,272 (29.03%)	12.72
3	Computer science interdisciplinary applications	46 (13.73%)	533 (12.17%)	11.59
4	Medical informatics	38 (11.34%)	490 (11.18%)	12.89
5	Computer science information systems	34 (10.15%)	342 (7.81%)	10.06
6	Mathematical computatonal biology	33 (9.85%)	505 (11.53%)	15.30
7	Instruments instrumentation	32 (9.55%)	468 (10.68%)	14.63
8	Computer science artificial intelligence	30 (8.96%)	392 (8.95%)	13.07
9	Physiology	20 (5.97%)	291 (6.64%)	14.55
10	Rehabilitation	19 (5.67%)	234 (5.34%)	12.32

Figures

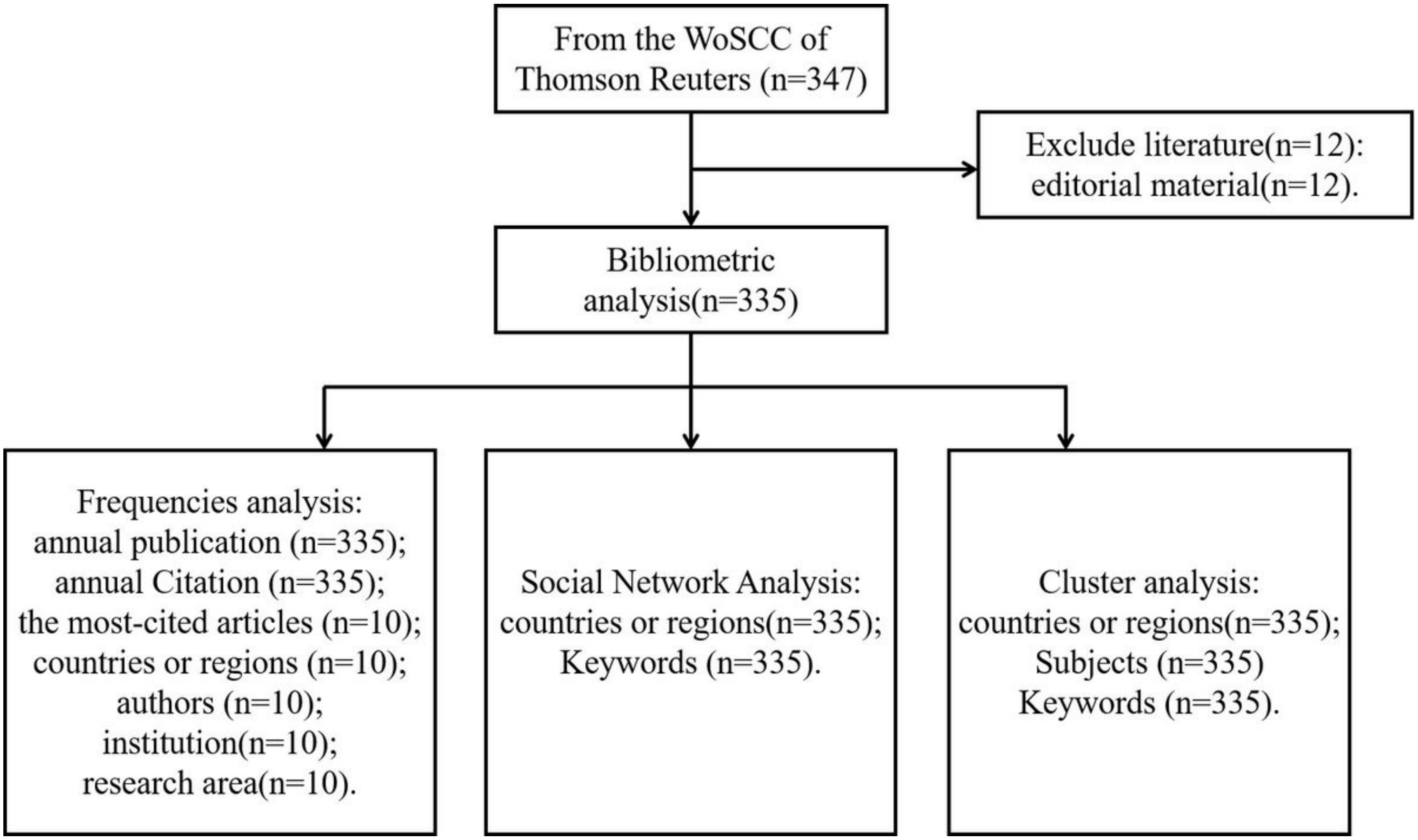

Figure 1

Guidelines Flow Diagram.

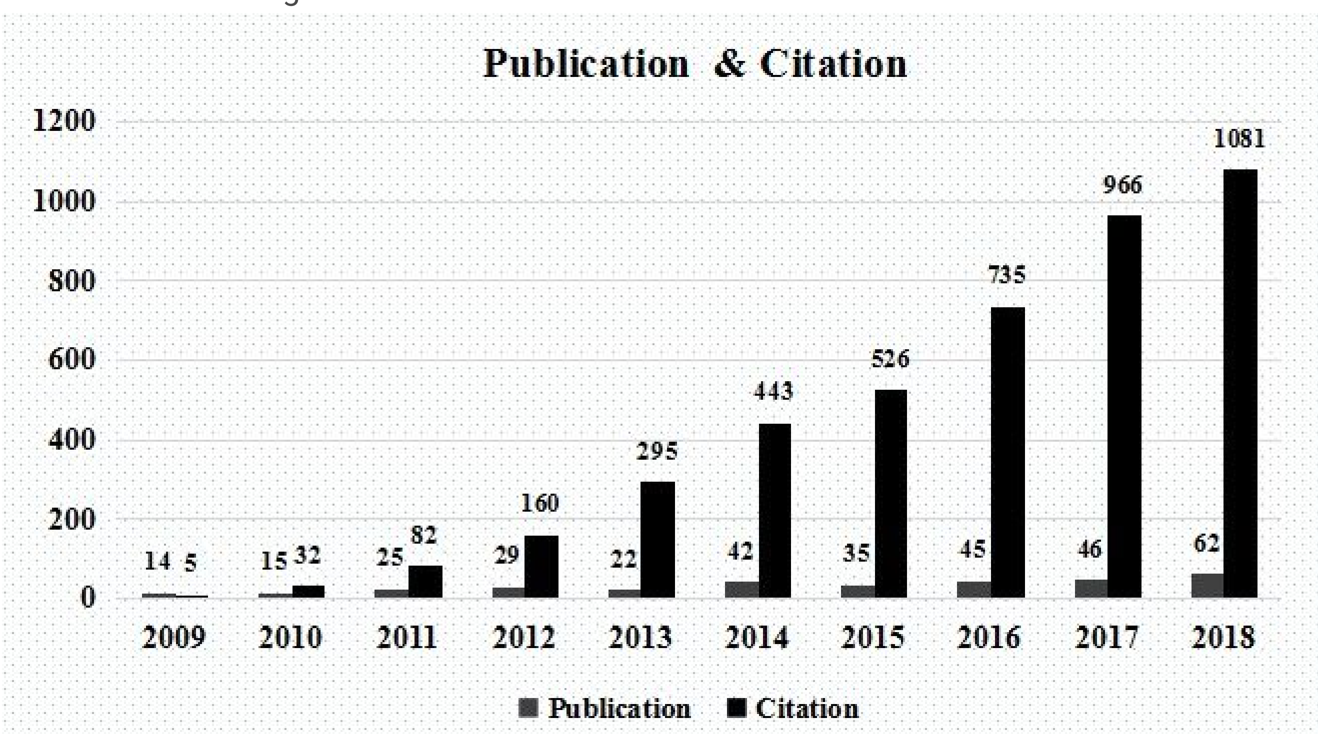

Figure 2

The number of publication and citation from 2009 to 2018.

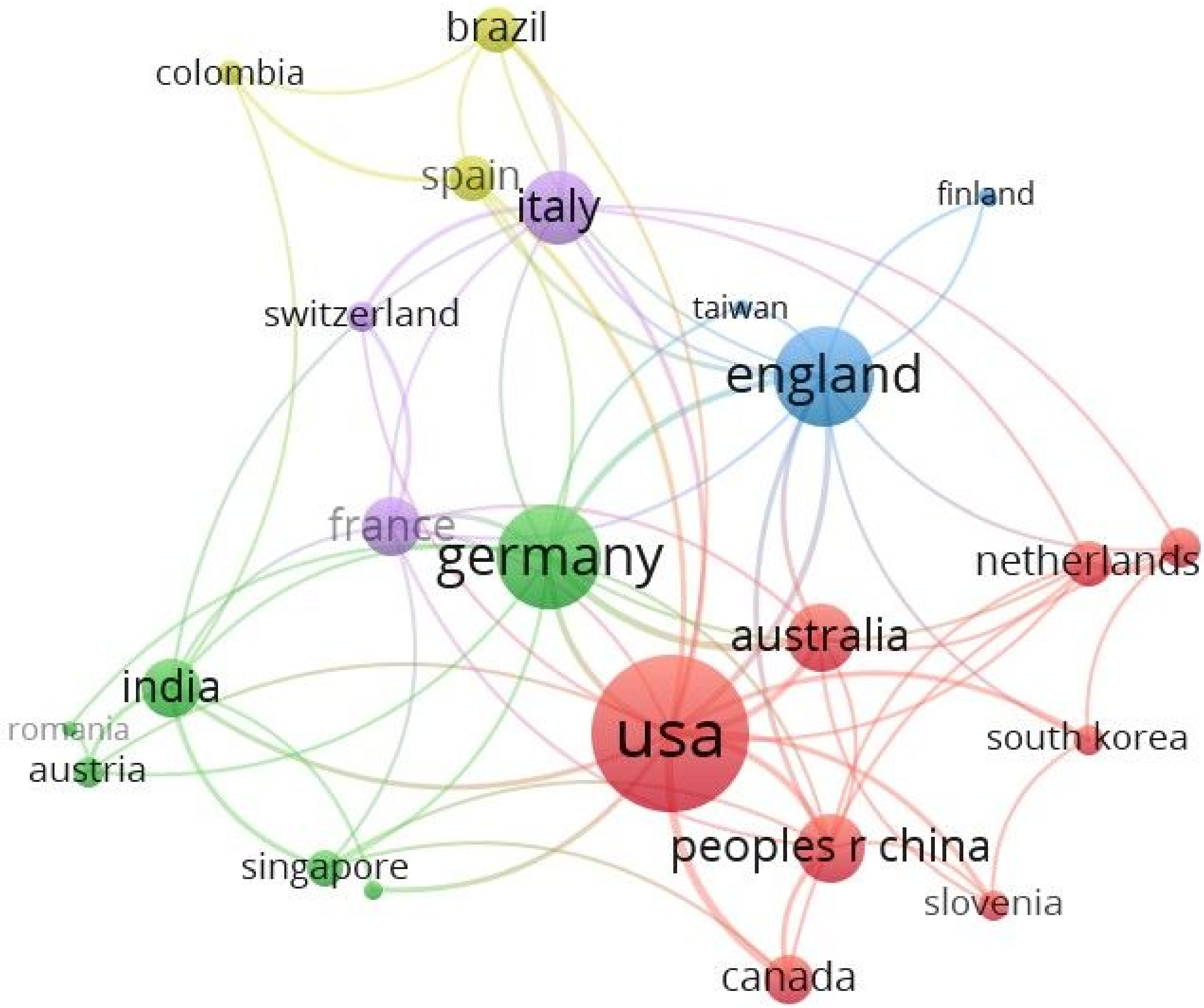

Figure 3

The national collaboration network of biomedical signal processing.

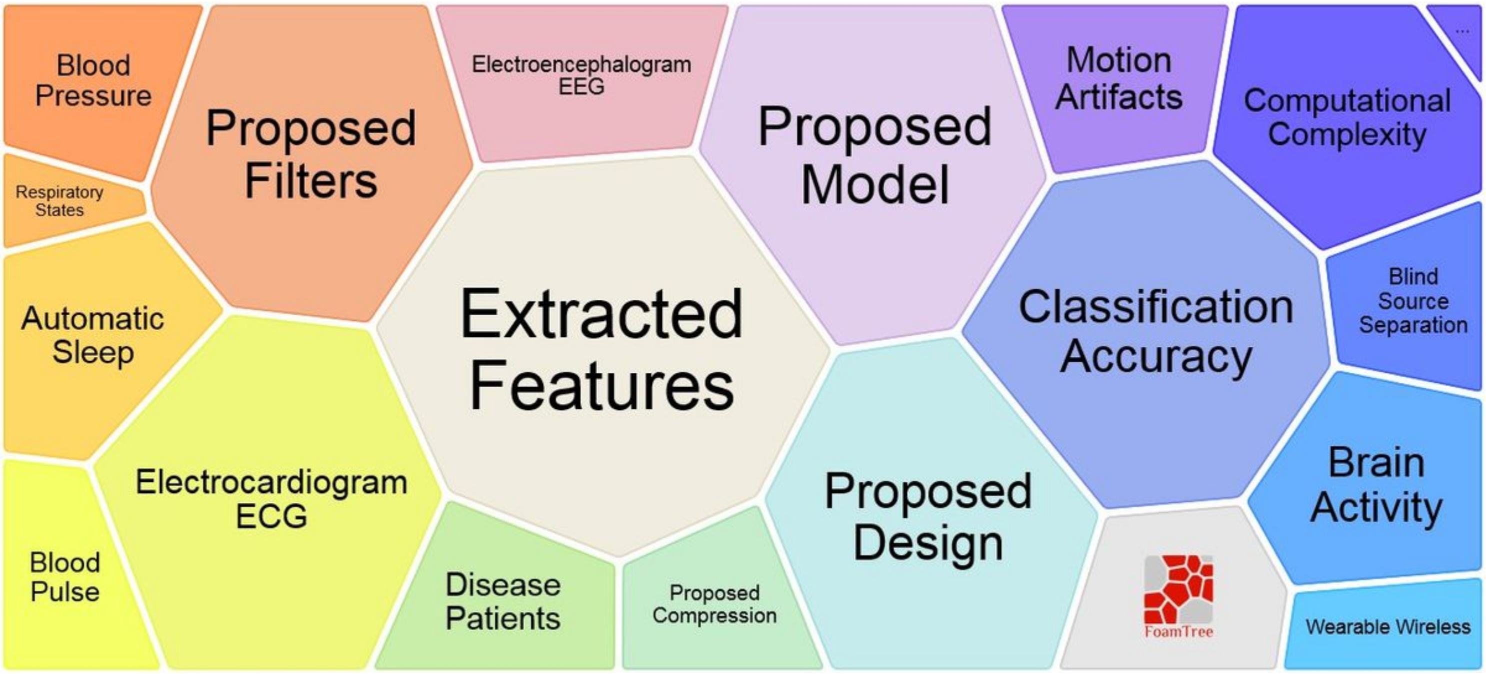

Figure 4

The terms clusters of biomedical signal processing.

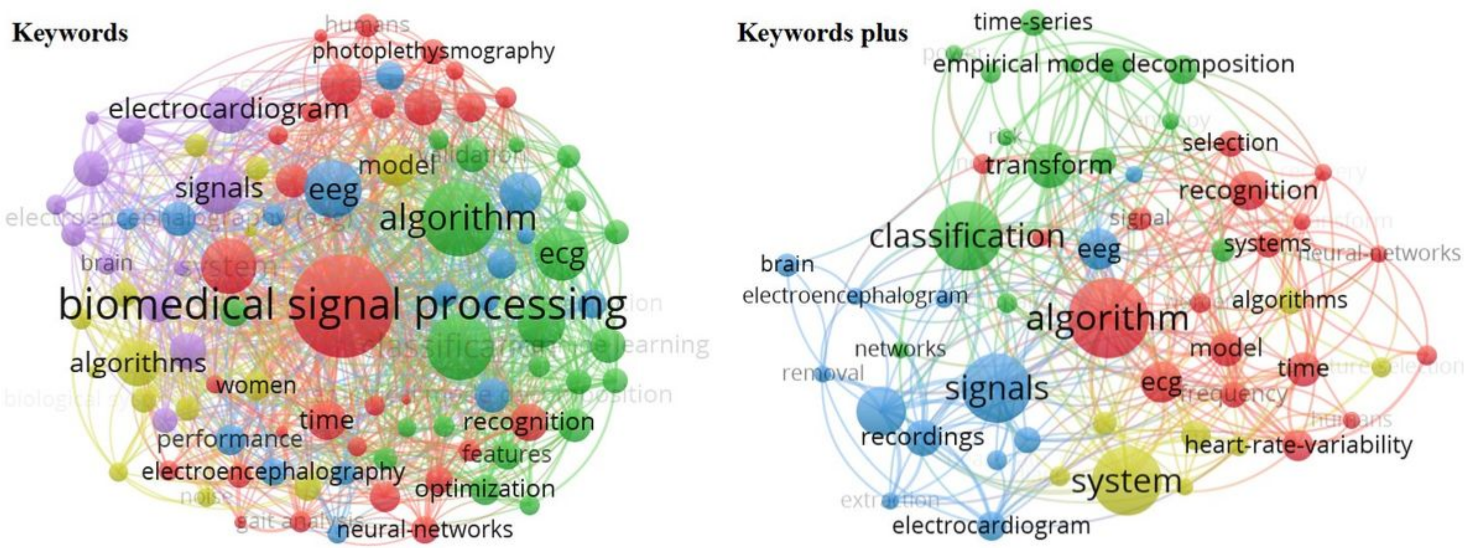

Figure 5

The network of keywords on biomedical signal processing.