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Research article

Scientific profile of brain–computer interfaces: Bibliometric analysis in a 10-year period

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HIGHLIGHTS

- Brain–computer interface (BCI)/Brain–machine interface (BMI) research and the relevant literature have expanded.
- Analysis of highly cited articles can help identify outstanding scientific studies.
- We investigated 100 highly cited BCI papers in the past 10 years, which can help distinguish between incremental and transformational studies.
- It provides insights into priorities and trends for guiding future BCI studies.

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ABSTRACT

Background: With the tremendous advances in the field of brain–computer interfaces (BCI), the literature in this field has grown exponentially; examination of highly cited articles is a tool that can help identify outstanding scientific studies and landmark papers. This study examined the characteristics of 100 highly cited BCI papers over the past 10 years.
Methods: The Web of Science was searched for highly cited papers related to BCI research published from 2006 to 2015. The top 100 highly cited articles were identified. The number of citations and countries, and the corresponding institutions, year of publication, study design, and research area were noted and analyzed.
Results: The 100 highly cited articles had a mean of 137.1(SE: 15.38) citations. These articles were published in 45 high-impact journals, and mostly in *TRANSACTIONS ON BIOMEDICAL ENGINEERING* ($n = 14$). Of the 100 articles, 72 were original articles and the rest were review articles. These articles came from 15 countries, with the USA contributing most of the highly cited articles ($n = 52$). Fifty-seven institutions produced these 100 highly cited articles, led by Duke University ($n = 7$).
Conclusions: This study provides a historical perspective on the progress in the field of BCI, allows recognition of the most influential reports, and provides useful information that can indicate areas requiring further investigation.

1. Introduction

Brain–computer interfaces (BCI), also called brain–machine interfaces (BMI), can create a direct communication pathway between the brain and an external device. Research on BCI began in the 1970s [1]; following years of animal experimentation, the first report of a BCI device implanted in a human appeared in 1998 [2].

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In the last few decades, BCI has emerged as a rapidly developing research area, and studies have focused on researching, mapping, assisting, augmenting, or repairing human cognitive or sensory-motor functions [3]. BCI research usually involves collaboration of multidisciplinary teams of researchers, including those from the fields of neuroscience, orthopedics, rehabilitation, computer science, and engineering [4]. Thus, the BCI literature encompasses reports from numerous researchers varying in specialties and countries of origin, and appearing in a range of scientific journals.

With the development of internet-based search engines, many methods for searching for relevant medical literature are now available. However, the results of basic keyword or topic searches are often overwhelming and shed little light on the most relevant articles. The Institute for Scientific Information (ISI) initiated Science Citations as a systematic approach for evaluating the impact of scientific journals or researchers according to the number of times their works have been cited by other authors [5], and it is widely used to measure the impact of certain papers, helping researchers to find important articles in their area of interest rapidly. This type of analysis has been applied to literature on different specialties and research areas [6–11], and there were earlier bibliometric analyses of the BCI literature, included years from 1990 to 2009[12,13], However, since this is a rapidly growing research area, little is currently known about the most frequently cited articles that are specifically related to BCI research in the latest decade.

Therefore, the purpose of this study was to identify the 100 most highly cited articles in the BCI field in the past 10 years, in an effort to evaluate important contributions to the literature in this promising area.

2. Materials and methods

Thomson Reuter's Web of Science was queried through the Harvard Library Portal, on one specific day, January 1, 2016, to avoid any changes in citation rate as far as possible, for all articles related to BCI published from 2006 to 2015. Different combination of the words "brain," "user," "mind," "machine," "computer," "communication," "interface," "BMI," and "BCI" were used, and the results were ranked by the total citation number. The terms "neural prosthetics" and "neuroprosthetics" were also used as search terms, in order to exclude some prosthetics that are only linked to other parts of the nervous system, such as the peripheral nerves, while the term BCI usually designates an interface with the central nervous system [8]. The full texts of these reports were mainly obtained from PubMed, EMBASE, and Medline. When full-text articles were not available, online abstracts were used.

Data inclusion criteria were as follows: (a) peer-reviewed articles on BCI research published and indexed in the Web of Science and (b) original research articles and review articles. Exclusion criteria were (a) patents, books, manuals, and non-biomedical publications, and (b) conference abstracts and case reports.

The 100 most highly cited articles were then identified based on the number of citations, and those published in the past 2 years were also considered. Owing to differences in time since publication, annual citations rates were also defined. Articles were selected by reading the abstract to gauge whether they were related to BCI, and the following data were extracted from each of the articles: title, year of publication, last correspond author and his/her first institution, country of origin, journal name, number of citations, type of study, research topic and keywords of study.

Statistical analysis was performed using R version 3.2.3 (Wooden Christmas-Tree). Statistically significant differences were identified using a non-parametric ANOVA analysis with an alpha level of 0.05. CiteSpace version 4.0 was used to visualize trends and patterns in BCI research [14–16].

3. Results

The 100 most highly cited articles on BCI research in Web of Knowledge were listed in Supplemental Materials (Table S1) in descending order of the total citation numbers they have. The 100 papers obtained a mean of 137.1 (SE 15.38) citations per article, the top one received 1294 citations (Hochberg, LR et al., 2006, *Nature*) [17]. Annually, the 100 highly cited articles received average 19.45 (SE 1.92) citations per paper (range, 5.40 to 129.40).

3.1. Countries and institutions of origin

The 100 articles originated from 16 different countries (Fig. 1); most (n = 48) studies were from the USA, followed by Germany (n = 19). Five studies were from Singapore; four from Switzerland and Austria; three each from France, England, Canada, and China; and one each from Sweden, Spain, the Netherlands, Japan, Israel, and Italy. Even though we used no language restrictions, all 100 studies were published in English.

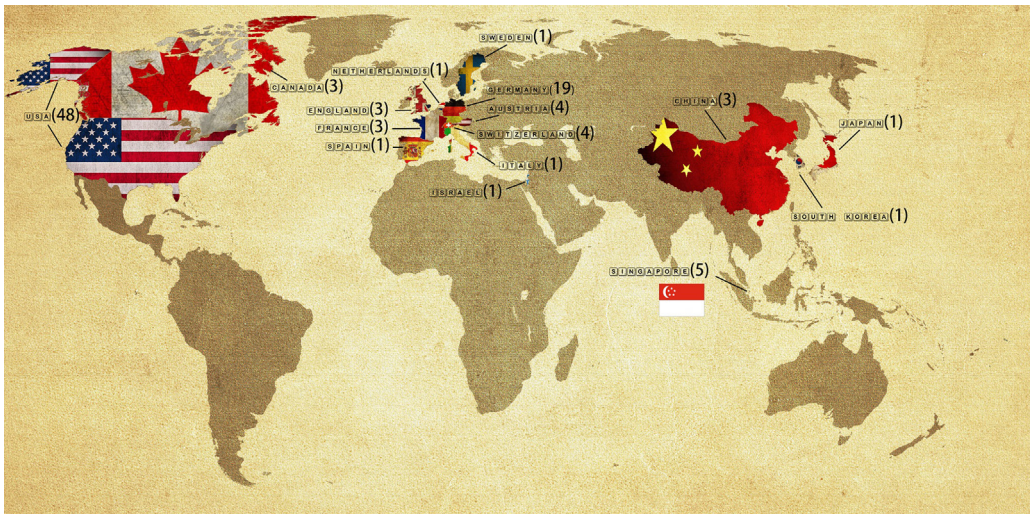

Fig. 1. Distribution of countries from which the 100 most highly cited brain-computer interface research articles originated from 2006 to 2015.