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Review

The bootstrap: A technique for data-driven statistics. Using computer-intensive analyses to explore experimental data

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Abstract

Background: The concept of resampling data – more commonly referred to as bootstrapping – has been in use for more than three decades. Bootstrapping has considerable theoretical advantages when it is applied to non-Gaussian data. Most of the published literature is concerned with the mathematical aspects of the bootstrap but increasingly this technique is being utilized in medical and other fields.
Methods: I reviewed the published literature following a 1994 publication assessing the transfer of technology, including the bootstrap, to the biomedical literature.
Results: In the ten-year period following that 1994 paper there were 1679 published references to the technique in Medline. In that same time period the following citations were found in the four major medical journals—*British Medical Journal* (48), *JAMA* (51), *Lancet* (52) and the *New England Journal of Medicine* (45).
Content: I introduce the basic theory of the bootstrap, the jackknife, and permutation tests. The bootstrap is used to estimate the accuracy of an estimator such as the standard error, a confidence interval, or the bias of an estimator. The technique may be useful for analysing smallish expensive-to-collect data sets where prior information is sparse, distributional assumptions are unclear, and where further data may be difficult to acquire. Some of the elementary uses of bootstrapping are illustrated by considering the calculation of confidence intervals such as for reference ranges or for experimental data findings, hypothesis testing such as comparing experimental findings, linear regression, and correlation when studying association and prediction of variables, non-linear regression such as used in immunoassay techniques, and ROC curve processing.
Conclusions: These techniques can supplement current nonparametric statistical methods and should be included, where appropriate, in the armamentarium of data processing methodologies.

Keywords: Bootstrap; Computer-intensive methods; Jackknife; Non-parametric statistics; Permutation tests; Random number generation

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1. Introduction

In a 1994 review Altman and Goodman [1] identified influential statistical articles and the time pattern of their citations in the medical literature. One such article described the bootstrap [2]—the topic of this review. I used an Ovid Technologies Medline keyword search ["bootstrap" or "resampling"] for the period 1995 to 2004 to assess the subsequent pattern of citations in the medical literature and recovered 1679 references.[1] These citations increased year-by-year since 1995 (Fig. 1). I also performed a full-text search (numbers of citations in parenthesis) of research articles in the journals *BMJ* (48), *JAMA* (51), *Lancet* (52), and the *New England Journal of Medicine* (45) over the same period (due to archive limitations some of these searches were for shorter periods). These findings suggest that bootstrap methods are increasingly

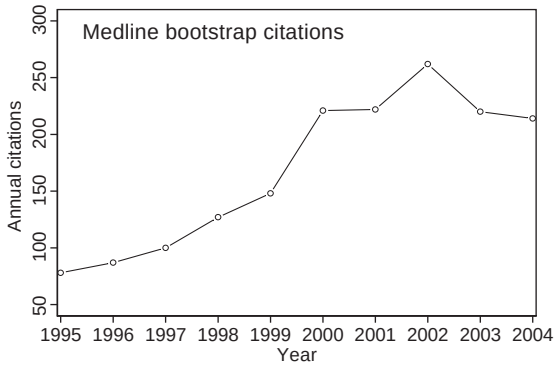

Fig. 1. The number of annual Medline citations for the search terms "bootstrap" or "resampling" for the period 1995 to 2003.

[1] These search terms do not recover all citations as they are not presently MeSH (Medical Subject Headings) indexing terms.