LITERATURE REVIEW: DESIGN OF EXPERIMENTS IN FINITE ELEMENT ANALYSIS SCOLIOSIS AND SPINAL PROCEDURE

Shreya Sivakumar

Sian Mcgarva

Maha Ead

Dr. Kajsa Duke

August 13, 2021

Abstract

Design of Experiments (DOE) refers to the way in which a scientific experiment is conducted. By analyzing five different computer-simulated spinal technique experiments it is clear to see the differences and similarities between the conducted experiments. Factorial analysis is used to describe the different techniques and simulations needed for the completion and efficiency of the experiments.

This paper analyzes five different spinal experiments, from an initial 163 studies cited by Dr. Dar, and compares them to a 60% factor significance average extracted from Dr. Fazilat Dar's study on Finite Element Analysis (FEA). Dr. Dar's paper's purpose was to examine the different statistical methods used in FEA, and Factorial Design in particular. Additionally, the study compares the extracted results to a paper on Data from Factorial Experiments written by Li et al. in 2006, where a 40% significance average was found. The three methods of factorial analysis that were considered are full factorial, fractional factorial, and Taguchi designs. Each of these approaches have different ways of determining main interactions and the significance of events and various factors.

The results of this review showed the efficiency of each of the five studies in terms of DOE. In comparison to Dr. Fazilat Dar's paper in 2002, two of the experiments were more efficient and three were less efficient. On the other hand, when the results are compared to Dr. Li's paper, three out of five of the papers were more efficient.

Introduction

Design of Experiments (DOE) is a sector of statistics and scientific research that revolves around analyzing data and conducting controlled tests. Within DOE, a form of experiment called Factorial Design is utilized to manipulate and vary multiple factors. Factorial Design allows researchers to conduct experiments at higher efficiency levels. Fractional factorial designs provide more information while running fewer tests, typically at a lower cost. This approach permits fast discovery of ideal conditions and the examination of further factors with no added expenses [1].

Design of Experiments is commonly used in computer simulated experiments. The technique is less commonly used in biomechanics, and even less prevalent in scoliosis and spinal patients. Given its low prevalence, it is important to analyze the efficiency of the data in DOE spinal research.

Factorial Design consists of various methods and approaches. The three methods that are of focus are full factorial, fractional factorial, and Taguchi approaches.

A full factorial design is a structured design style testing every possible combination that permits estimation of interactions and significance of different events. This style is effective but depends on many controlled tests being conducted as the variables increase. Additionally, with a vast number of factors, this method is time consuming [2].

A fractional factorial design aims to choose a subset of runs from a full factorial design as its controlled tests. The purpose of fractional factorial methods is to examine the cause-and-effect relationships in any given experimental procedure. If done efficiently, a fractional or partial factorial design can produce the same conclusions as a full factorial design but with fewer resources and less time [2].

The Taguchi method, developed by engineer and statistician Genichi Taguchi, is a category in fractional factorial design. Like typical fractional factorial design, this method aims to produce efficient results with the usage of less time and resources. However, the Taguchi method is most prevalent in engineering and intends to reduce failures and defects in all areas of experimental design technology [3].

In 2002, Dr. Fazilat Dar published a paper on Statistical Analysis on Finite Element Analysis (FEA) [2]. The paper focused on statistics, probability, and factorial design. The outcomes of the paper presented itself as having a 60% overall average of significant factors. This was a fundamental paper showing DOE applied to biomechanics. It has been cited over 160 times and provided the basis for this literature review. In addition, a paper by Dr. Li in 2006 found that about 40% of the main effects in DOE experiments were significant. Comparisons to efficiency of DOE in scoliosis and spinal research will be made in each of the five controlled experiments using Dr. Dar's average of 60% and Dr. Li's average of 40% for significant factors [2].

An initial 163 papers involving DOE were reviewed. From this set of papers, five different scoliosis and spinal research papers have been analyzed, categorized, and examined. By looking at the number of input factors, controlled tests, output factors, and the overall average of significant variables, a statistical analysis can be conducted to determine the efficiency of each experiment's DOE approach.

Methods

The five studies were chosen based on the abundance of information compared to other DOE studies in scoliosis and spinal research. These five studies had all the information regarding input factors, output factors, methods used, and average of significant variables present. There were approximately five scoliosis and spinal papers that were excluded due to the lack of information provided. Once a general analysis was done to determine that these papers had too little information, they were extracted. None of the research conducted in this study includes statistics from any of the extracted papers. A handful of other papers were either inaccessible or could not be found. These five papers were chosen because the studies conducted best summarize DOE in FEA spinal research.

Results

A summary of the papers reviewed are shown in Table 1. The author, year, number of input and output factors, tests, methods used, and average of significant factors are included. The purpose of this table is to narrow down the aspects of the study with the most importance.

Table 1: Summary of papers reviewed

Paper	Author/Year	Input Factors	Runs	Method	Output Factors	Average of Significant Factors
1	Duke/2008	6	32	½ Factorial	10	56.67%
2	Amaritsakul/2013	6	100	Taguchi	1	100.00%
3	La Barbera/2014	14	*Unknown*	Fractional Factorial	1	21.43%
4	Ghezelbash/2016	4	450	Full Factorial	4	25.00%
5	La Barbera/2021	5	1080	Full Factorial	3	73.33%

The pie chart below portrays the percentage of fractional and full factorial methods used in the five different experimental procedures. This information is useful because it can help make conclusions regarding the efficiency of each experiment based on the factorial design method used.

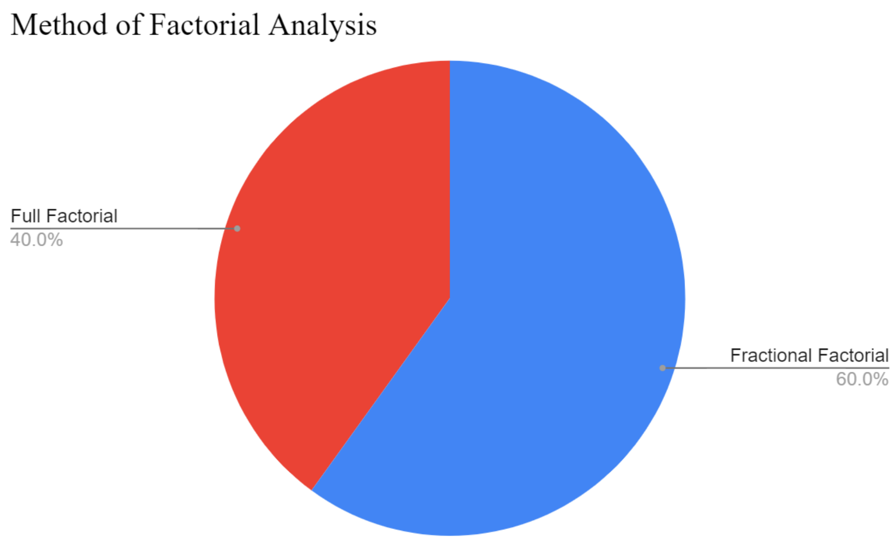

Figure 1: Pie chart showing percentages of full and fractional factorial designs derived from the five derived experiments

The bar graph below shows the efficiency of overall significance of main events in each of the considered studies. This information is used to compare the efficiencies from the different studies.

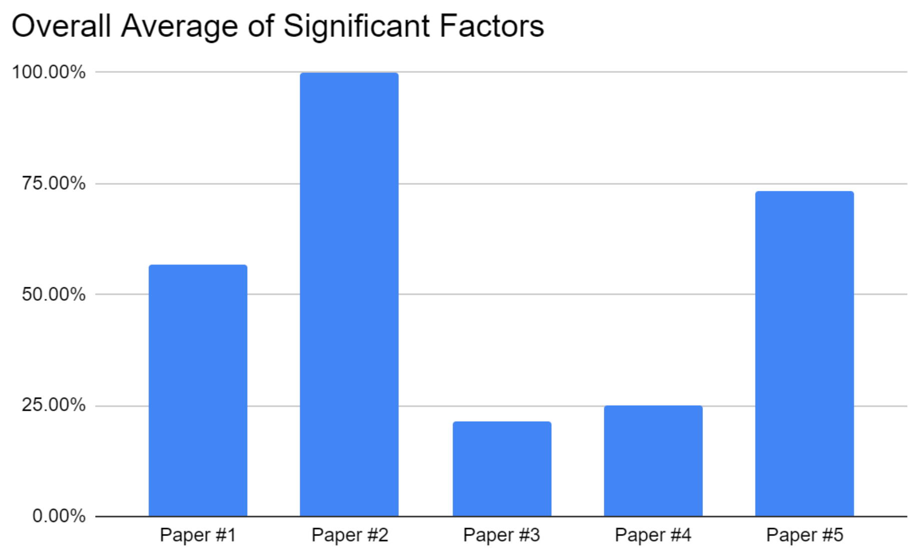

Figure 2: Bar graph of overall average of important input factors on output factors

Discussion and Conclusion

The first experiment, authored and conducted by Dr. Duke in 2008, took a fractional factorial approach with 32 runs. The experiment consisted of six input factors and ten output factors. The overall average of significant input factors on the output factors from this experiment was 56.67% [4]. In terms of DOE, Dr. Duke's experiment with utilization of a half fractional factorial, is slightly less efficient than Dr. Dar's experiment in terms of the importance of each input factor relative to the output factors. However, Dr. Duke's study was more effective than Dr. Li's experiment in 2006.

The second experiment, directed by Dr. Amaritsakul in 2013, used the robust Taguchi method with 100 controlled simulations. The study had six input factors and one output factor. The percent average for the number of important factors was 100.00%. As presented in statistics, all factors for this experiment were significant. However, this is easier to achieve since the experiment only consisted of one output factor [5]. Though Dr. Amaritsakul's study is proven to be more efficient than Dr. Li's and Dr. Dar's papers in terms of DOE; it cannot be concluded that the experiment would maintain its effectiveness if more factors and levels were added or considered.

The third experiment by Dr. La Barbera in 2014 utilized a fractional factorial method with an unknown number of runs. The study consisted of 14 input factors and only one output factor. The average of significance in variables was 24.43%. The efficiency is lower in this study because of the larger amount of input variables. Therefore, this paper is less efficient than both Li et al. and Dr. Fazilat Dar's original paper [6].

The fourth experiment conducted by Dr. Ghezelbash in 2016 took a full factorial approach with 450 controlled tests. There were four input factors, four output factors, and the statistical significance of the input variables relative to the outputs was 25.00%. Regarding DOE, this study was less efficient than Dr. Li's study in 2006 and Dr. Dar's study in 2002 [7].

The fifth and most recent experiment, authored by Dr. La Barbera in 2021 also took on a full factorial approach. The study had five input factors and three output factors, with an overall factor significance average of 73.33%. This study was more effective than that of Dr. Dar's and Dr. Li's [8].

The range of efficiency in this paper was 75.57%, as the least efficient study had an effectiveness rate of 24.43%, and the most efficient study was 100% effective. In the study that Dr. Li conducted back in 2006, the range of efficiency was 100% meaning there was more diversity in how efficient each of the papers were.

At first, a hypothesis was made predicting that studies with fewer output factors had a higher probability of being more efficient since less possibilities were being considered. However, this turned out not to be the case. This is proven by Dr. La Barbera's study in 2014, where only one output factor was considered. Although the experiment consisted of low output quantities, since the input quantities were large, the study ultimately became less efficient. Therefore, it can be concluded that lower output factors combined with higher input factors does not result in a more efficient study in terms of DOE.

Acknowledgements

I would like to extend my deepest gratitude to my supervisor and principal investigator, Dr. Kajsa Duke. She has provided me with incredible learning opportunities and has pushed me beyond my capabilities. Her consistent encouragement, enthusiasm, and generosity not only kept me motivated throughout the duration of the program, but also inspired me to pursue my passions in engineering. I am grateful and very fortunate to have learned from her.

I would also like to express my appreciation for PhD candidate Maha Ead. She is such a positive role model, and I will treasure her guidance throughout my academic journey.

A special thank you to Threshold Impact for funding my research project and the University of Alberta for providing me with this incredible opportunity.

Finally, I am grateful for the WISEST Summer Research Program. From the amazing coordinators to my extraordinary mentors and my inspiring peers, everyone at WISEST has welcomed me with open arms. I could not have successfully conducted this research without their help.

Literature Cited

[1] L. Eriksson, *Design of experiments : principles and applications*. Umetrics AB, 1999.

[2] F. H. Dar, J. R. Meakin, and R. M. Aspden, "Statistical methods in finite element analysis," 2002.

[3] K. Khan, "An Overview on Taguchi Method." [Online]. Available: https://www.researchgate.net/publication/265282800

[4] K. Duke, C. E. Aubin, J. Dansereau, and H. Labelle, "Computer simulation for the optimization of patient positioning in spinal deformity instrumentation surgery," *Medical and Biological Engineering and Computing*, vol. 46, no. 1, pp. 33–41, Jan. 2008, doi: 10.1007/s11517-007-0265-z.

[5] Y. Amaritsakul, C. K. Chao, and J. Lin, "Multiobjective optimization design of spinal pedicle screws using neural networks and genetic algorithm: Mathematical models and mechanical validation," *Computational and Mathematical Methods in Medicine*, vol. 2013, 2013, doi: 10.1155/2013/462875.

[6] L. la Barbera, F. Galbusera, T. Villa, F. Costa, and H. J. Wilke, "ASTM F1717 standard for the preclinical evaluation of posterior spinal fixators: Can we improve it?," *Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine*, vol. 228, no. 10, pp. 1014–1026, Oct. 2014, doi: 10.1177/0954411914554244.

[7] F. Ghezelbash, A. Shirazi-Adl, N. Arjmand, Z. El-Ouaaid, A. Plamondon, and J. R. Meakin, "Effects of sex, age, body height and body weight on spinal loads: Sensitivity analyses in a subject-specific trunk musculoskeletal model," *Journal of Biomechanics*, vol. 49, no. 14, pp. 3492–3501, Oct. 2016, doi: 10.1016/j.jbiomech.2016.09.026.

[8] L. la Barbera, A. N. Larson, J. Rawlinson, and C. E. Aubin, "In silico patient-specific optimization of correction strategies for thoracic adolescent idiopathic scoliosis," *Clinical Biomechanics*, vol. 81, Jan. 2021, doi: 10.1016/j.clinbiomech.2020.105200.