

**AC 2007-2080: COMPUTER-AIDED INSTRUCTION OF FUNDAMENTAL
MECHANICS COURSES USING MATLAB**

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Abstract

Fundamental mechanics courses including statics, dynamics, strength of materials, and design of machine elements are typically taught for engineering students in lecture and discussion format using traditional techniques. These fundamental mechanics courses are mostly involved with many time-intensive engineering calculations and analysis procedures, eliciting tedium, complexity, and computational burden. A couple of MATLAB toolboxes have been developed over many years for these courses. They include Equilibrium Toolbox (EQT) for 2D & 3D vector and equilibrium analysis of particles, rigid bodies and structures, and Mechanical Design Toolbox (MDT) for stress analysis and design of various mechanical components. The toolboxes are written in MATLAB by taking advantage of its user-friendly interactive graphic user interface, multiple document interface and compilation capabilities into windows application programs for easy deployment with four rationales in mind – simplicity, computational efficiency, flexibility, and convenience. They are not just intended to replace hand calculations like some textbook specific programs but to learn various analysis procedures in step-by-step interactive tutorial fashion and to conduct large-scale design simulations for open-ended design problems. A couple of pilot studies were conducted with students at various levels to test the effectiveness of the toolboxes in teaching and learning the fundamental mechanics courses. It is suggested that use of such toolboxes in laboratory setting would be most effective. This paper will present experiences how the toolboxes have been developed and how they are efficiently used in teaching and learning the fundamental mechanics courses.

Introduction

The fundamental mechanics course sequence including statics, dynamics, strength of materials, kinematics of machinery, and design of machine elements are hardcore classes in most mechanical engineering curriculum beginning at the sophomore year. These courses have been a bottleneck due to significant numbers of failures and repeats. For example, in our ME departmental survey at California State Polytechnic University, Pomona with 319 students who took the vector statics course from various majors during fall 2001 and winter 2002 quarters, it was found that over 44% of them did not have the passing grades, and that was a small increase from 40% taken from the survey during the academic year 2000-2001. The high repeat and failure rates significantly hamper the students to move up to their curricula, resulting in a high attrition rate of the students.

These fundamental mechanics courses are mostly involved with many time-intensive engineering calculations and analysis procedures, eliciting tedium, complexity, and computational burden. The most common pedagogy of the fundamental mechanics courses is a face-to-face classroom lecture and discussion format using traditional techniques such as blackboard, overhead transparencies, etc. Many students feel very complicated in learning these

fundamental subjects in this format, resulting in poor class retention and completion. It is postulated that computational tools can increase productivity of teaching and learning the fundamental mechanics courses, since they allow students to unload the computational burden and to conduct various thought experiments and simulations for creatively solving mechanics problems.

Most mechanics problems often can be solved by hand in conjunction with generic mathematics computer packages such as MS Excel spreadsheet, MathCAD, MAPLE, MATLAB, TK Solver, etc. However, this mode of solution is more or less unrealistic since it is yet a challenge for most undergraduate engineering students. There are also commercial high-end computational software tools that can be used for these courses but they are too specialized, expensive and complicated to be used in classroom setting. Other custom software tools are textbook-specific and lack of integrated functional capability and compatibility. Thus, there is a great need for comprehensive and integrated software tools for generic use in teaching and learning the fundamental mechanics courses. A lot of instructors are reluctant to use computational tools fearing incomplete understanding of the students on the subject matters and additional efforts for software development and thus deemphasize computer solutions. In a comprehensive review Kadiyala and Cryes demonstrated¹ that computer-based instruction (CBI) with the aid of recent information technologies could enhance the quality of teaching and learning when combined with sound pedagogy, good match of technology, techniques and objectives. This paper will present experiences in developing such toolboxes and their efficient use in teaching and learning the fundamental mechanics courses.

Development of MATLAB toolbox

A MATLAB toolbox is a collection of individual analysis modules supported by a software architecture that can allow an integrated analysis of multiple fundamental mechanics problems. Development of MATLAB toolbox is a meritorious choice for many reasons. Its versatile computational power, easy graphical user interface, convenient GUI development tools (GUIDE function), easy deployment (MATLAB compiler) and availability of numerous existing toolboxes for seamless integration have lead to its wide-use amongst universities and industry.^{2,3} The MATLAB GUI controls are very intuitive and provide an interactive learning environment so that the user can see immediately the impact of various parametric changes,⁴ resulting in proliferating GUI based analysis programs in many areas of science and engineering.^{5,6}

A couple of toolboxes have been developed using this *de facto* standard numerical analysis software for statics, strength of materials, and machine design by taking advantage of its user-friendly interactive graphic user interface (GUI), multiple document interface (MDI) and compilation capabilities into independent MS Windows applications so that students can run these programs at home without installing the MATLAB software on their computers. They include Equilibrium Toolbox (EQT) for 2D & 3D vector and equilibrium analysis of particles, rigid bodies and structures (Fig. 1, Table 1) and Mechanical Design Toolbox (MDT) for stress analysis and design of various mechanical components (Fig. 2, Table 2).



Figure 1 Equilibrium Toolbox (EQT). The main control interface consisting of nine analysis modules



Figure 2 Mechanical Design Toolbox (MDT). The main control interface and description of analysis panels

Analysis Module Name	Analysis Procedures	Description
Basic Matrix Analysis	<ul style="list-style-type: none"> • Linear Equation • Determinant 	Up to six unknowns
Graphical Vector Analysis	<ul style="list-style-type: none"> • Two Vector Addition • Two Vector Subtraction • Vector Triangle • Vector Resolution 	Simple graphical 2D vector analysis using two vectors
Advanced Vector Analysis	<ul style="list-style-type: none"> • Scalar Product • Dot Product • Triple Scalar Product • Triple Vector Product • Vector Resultant • Vector Resolution • Vector Calculator 	Comprehensive 2D & 3D vector analysis
Moment Analysis	<ul style="list-style-type: none"> • Resultant Moment • Moment along an Axis • Resultant Force-Couple • Zero Couple Location 	
Force Equilibrium	<ul style="list-style-type: none"> • 2D Force Equilibrium • 3D Force Equilibrium 	
Force-Moment Equilibrium Analysis	<ul style="list-style-type: none"> • 2D Force & Moment Equilibrium • 3D Force & Moment Equilibrium 	
Force Equilibrium about an Axis Analysis	<ul style="list-style-type: none"> • Force Equilibrium about an Axis Analysis 	Special case of 3D equilibrium problems
Truss Analysis	<ul style="list-style-type: none"> • Truss Force & Deflection Analysis 	
Frame Analysis	<ul style="list-style-type: none"> • Frame Equilibrium Analysis 	

Table 1 Analysis modules and procedures in Equilibrium Toolbox.

Analysis Panel Name	Analysis Procedures	Description
Stress Analysis Panel	<ul style="list-style-type: none"> • SFD&BMD/ Deflection Analysis • 2D Mohr Circle Analysis • 3D Mohr Circle Analysis • Combined Stress Analysis • Curved Beam Bending Analysis • Concentric Buckling Analysis • Eccentric Buckling Analysis 	Using singularity functions Axial/Torsion/Bending Various cross-sections
Shaft Design Analysis Panel	<ul style="list-style-type: none"> • Geometric Constraints Analysis • Static Strength Constraints Analysis • Fatigue Strength Constraints Analysis • Critical Speed Analysis 	Bearing slope constraints MSST/DET Gerber/Elliptic/Goodman/ Soderberg Dunkeley/ Rayleigh
Fasteners Panel	<ul style="list-style-type: none"> • Power Screw Mechanics Analysis • Tension Joints-Static Analysis • Tension Joints-Fatigue Analysis • Shear Joints Analysis 	ACME/ square threads Shigley/ Wileman's
Cylindrical Members Panel	<ul style="list-style-type: none"> • Thin-Walled Cylinder Analysis • Thick-Walled Cylinder Analysis • Rotating Cylinder Analysis • Press/Shrink Fit Analysis 	
Failure Analysis	<ul style="list-style-type: none"> • Static Stress Concentration Analysis • Fatigue Stress Concentration Analysis • Static Failure Analysis • Fatigue Failure Analysis 	Peterson's Book Neuber & Heywood Eqns DET/MSST/CM/BCM, etc Gerber/ Elliptic/Goodman/ Soderberg
Belt Analysis Panel	<ul style="list-style-type: none"> • Flat Belt Analysis • V-Belt Analysis 	
Slider Bearings Panel	<ul style="list-style-type: none"> • Slider Thrust Bearing Analysis • Slider Journal Bearing Analysis 	Using Hamrock's textbook
Helical Compression Springs Panel	<ul style="list-style-type: none"> • Helical Spring Kinematics Analysis • Static Design Analysis • Fatigue Design Analysis 	
Helical Extension Springs Panel	<ul style="list-style-type: none"> • Static Design Analysis • Fatigue Design Analysis 	
Helical Torsion Springs Panel	<ul style="list-style-type: none"> • Static Design Analysis • Fatigue Design Analysis 	
Contact & Lubrication Analysis Panel	<ul style="list-style-type: none"> • Hertz Elliptical Contact Analysis • Hertz Rectangular Contact Analysis • Minimum Film Thickness for Elliptical Contact Analysis • Minimum Film Thickness for Rectangular Contact Analysis • Minimum Film Thickness for Gear Contact Analysis 	For spherical ball bearings For cylindrical roller bearings
Spur Gear Analysis Panel	<ul style="list-style-type: none"> • Gear Kinematics Analysis • Allowable Gear Strength Analysis • AGMA Tooth Stress Analysis 	AGMA Gear Design Procedures
Helical Gear Analysis Panel	<ul style="list-style-type: none"> • Gear Kinematics Analysis • Allowable Gear Strength Analysis • AGMA Tooth Stress Analysis 	AGMA Gear Design Procedures

Table 2 Analysis panels and procedures in Mechanical Design Toolbox.

Rationales of the MATLAB toolbox development

The toolboxes have been programmed using MATLAB by taking into account the four rationales in mind – simplicity, computational efficiency, flexibility, and convenience.⁷ However, they are not merely intended to replace hand calculations but as an interactive learning aid to learn various analysis procedures in step-by-step interactive fashion and to conduct complex simulations for open-ended mechanics/ design problems. The four major rationales are

- a. Simplicity: To have GUI's for interactive input of analysis parameters and graphical and numerical presentation of the results, and to solve fundamental mechanics problems without writing a formal program. An analysis module often consists of menus, textboxes, pushbuttons, radiobuttons and lists to select/enter various input parameters (Fig. 3).

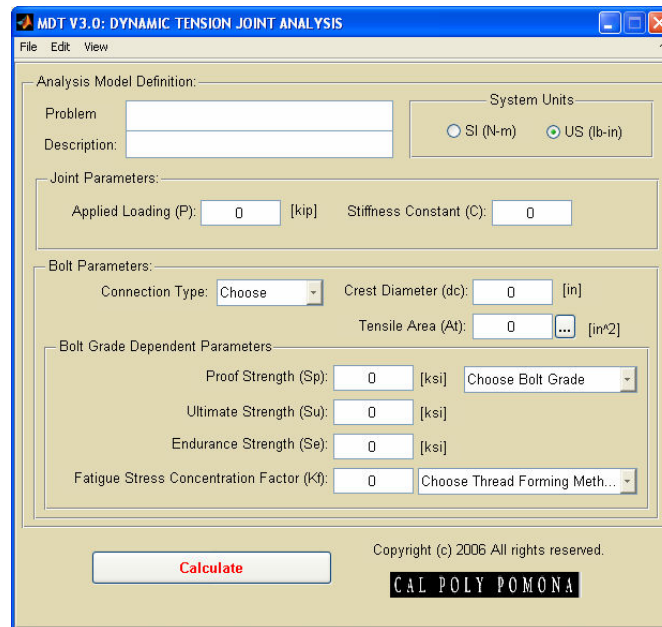


Figure 3 Typical graphic user interface of Mechanical Design Toolbox for interactive input of various analysis parameters.

- b. Computational Efficiency: To solve mechanics problems in a time-efficient manner by eliminating tables, charts, and tedious hand calculations (Fig. 4), to solve and optimize both implicit and explicit fundamental mechanics problems irrespective of the complexity of the governing equations (Fig. 4), and to simultaneously solve multiple analysis problems for integrated design projects.

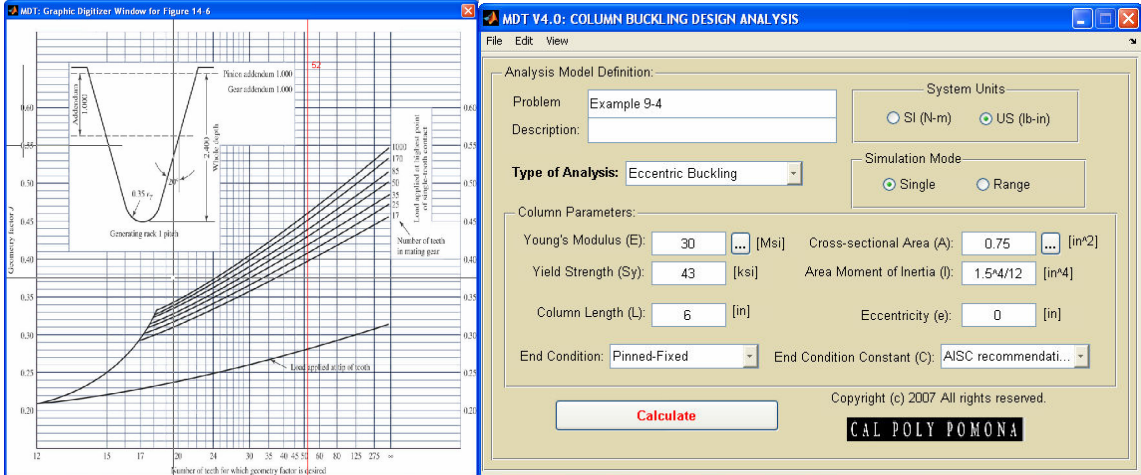


Figure 4 Interactive mouse-picking of spur gear geometry factor (J) directly from a graph in the AGMA tooth strength analysis module and nonlinear solution of an eccentric buckling problem in the column buckling analysis module

- c. **Flexibility:** To solve more than one type of mechanics problem using the same tool, to solve mechanics problems in integrated manners by simultaneously incorporating various tools, and to conduct design simulations with incremental change of the input variables to answer "What if...?" and "How can I...?" questions. Range simulations or sensitivity analysis can be done to get the mechanical response for a given range of a variable to understand the interactions between design variables (Fig.5).

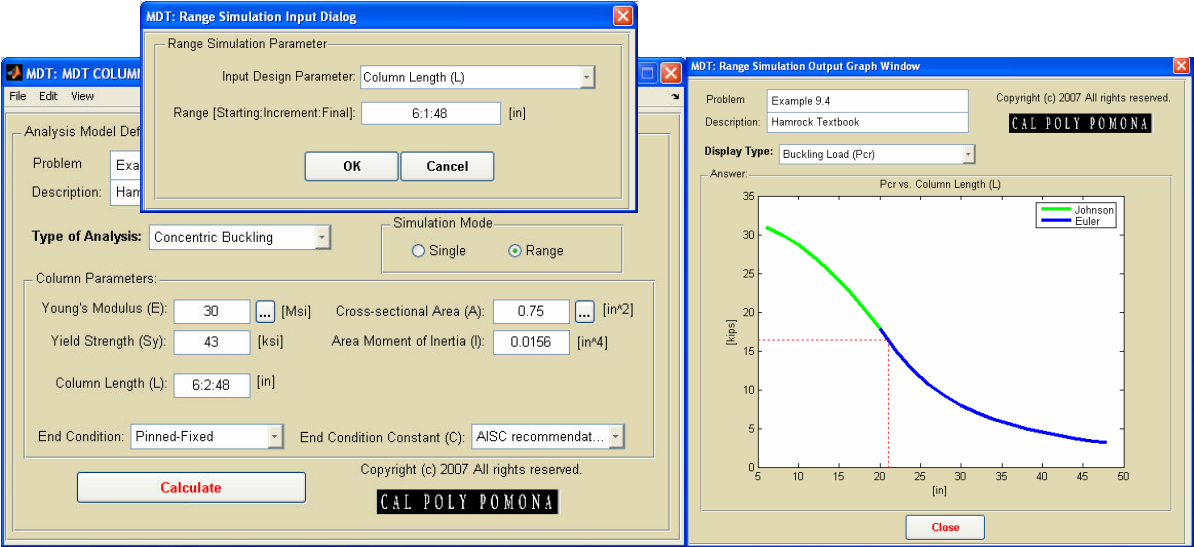


Figure 5 Range simulation of a concentric buckling problem for an interval of column length between 6 and 48 inches at intervals of 1 in. to the critical buckling load or stress

- d. **Convenience:** To generate an elegant engineering calculation report to validate various input parameters and intermediate results (Fig. 6) for comparison with hand-calculations, and to save and retrieve the analysis session for archival, submission, and future use.

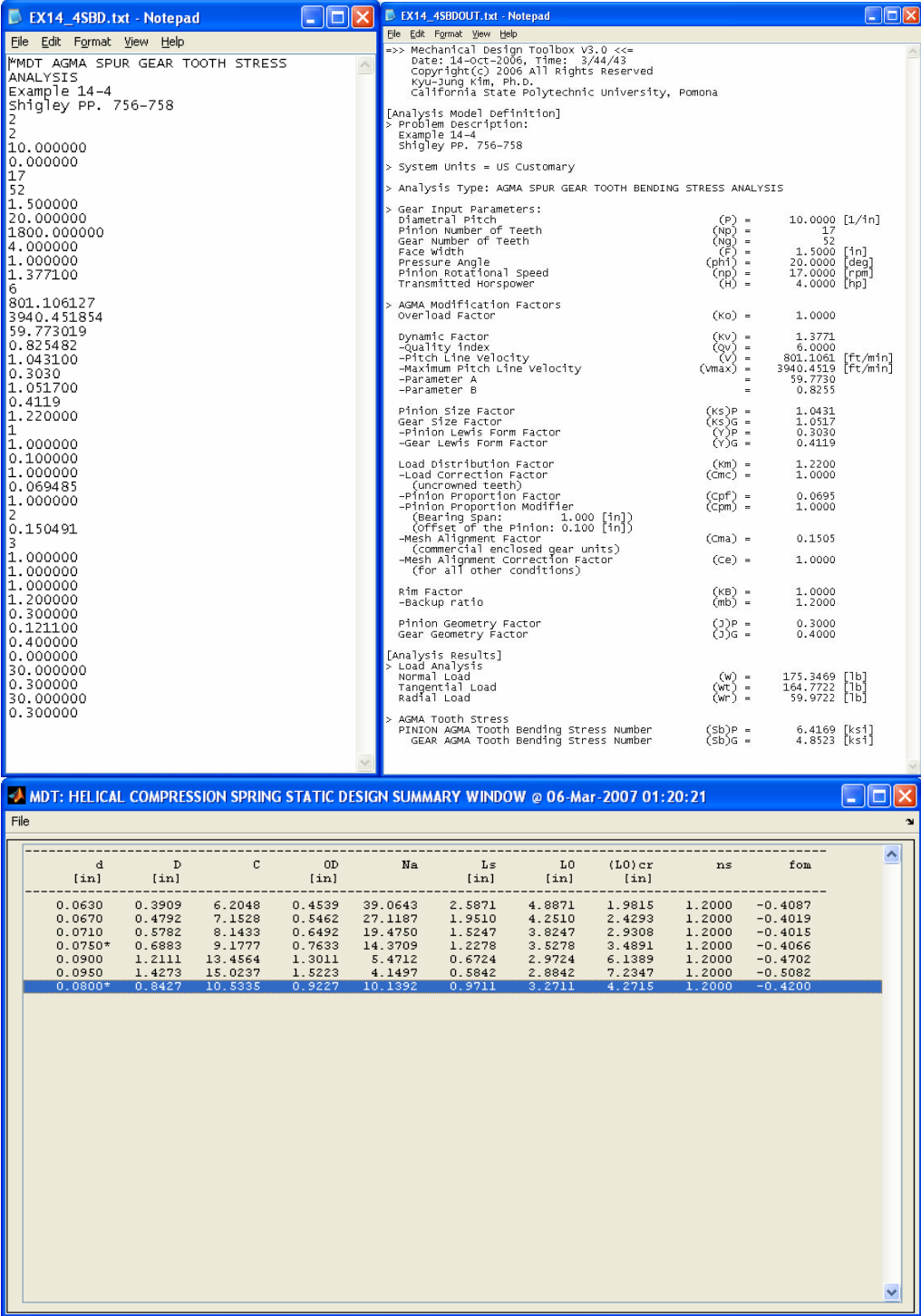


Figure 6 All the analysis input parameters and output results are saved into separate text files for validation of students' hand calculations. History of manual or automatic range simulation results are saved for static spring design analysis (Acceptable design is marked with *).

Classroom implementation of the MATLAB toolboxes

A couple of pilot efficacy assessment studies were conducted with students at various levels to test the effectiveness of the MATLAB toolboxes in teaching and learning the fundamental mechanics courses. In one study, the students in a sophomore-level vector statics course during winter 2005 quarter were asked to use the Equilibrium Toolbox (EQT) for their homework assignments for extra credit and take-home extra credit assignment for a midterm exam which were four open-ended computer problems from the Beer & Johnston's textbook.⁸ Even without any formal introduction to learn the EQT in the classroom, the students could use the toolbox without great difficulty along with online tutorials containing solutions of textbook examples using the EQT. A total of 24 out of 63 students submitted the computer solutions using the EQT with an average solution of 1.8 problems. Any more formal assessment was not made.

A more detailed pilot study was conducted at other institution for statistical efficacy assessment of the mechanical design toolbox (MDT) with two groups of students in two separate semesters in a design of machine elements (DME) course, which is a four-credit required course with two 75-minute lectures and a two-hour discussion per week. Assessments were made for scores of homework assignments and exams for two semesters one year apart. The former semester (Spring 2002) was taught as usual, whereas in the latter semester (Spring 2003) the MDT was used for demonstration in conjunction with hand calculation during the lectures and for student use during the discussion sections in a computer laboratory. The students were required to use the toolbox for twelve homework and computer assignments. The same sets of homework assignments and exams (two midterms and one final) with exactly the same questions were given to both groups of students. Though different graduate teaching assistants graded the homework assignments, the same instructor graded the exams with the same grading criteria. The statistical comparisons were made using the effect size and independent *t*-tests at the level of significance of $p=0.05$. The effect size (ES) is defined as the difference between the mean scores of two groups divided by the standard deviation of the control group.¹ An ES of 0.3 in a typical study is considered a moderate but significant effect.⁹

Twenty-four and twenty-five mechanical engineering seniors signed up for the courses in each semester, respectively. More students tended to submit homework assignments in the latter semester when use of MDT was required. There were 18 no submissions from 8 individual students in the latter semester, whereas 28 no submissions from 12 individual students in the former semester. Four homework assignment scores, ES less than -0.3, demonstrated reduction of the scores with the use of MDT. This was attributable to different graders and different grading criteria that solutions using the MDT were also part of the grade in the latter semester. However, the exam scores demonstrated statistically significant improvements (Fig. 5; $ES>0.9$ and $p<0.001$). Subsequently, the class average of the weighted total grades was significantly improved from 69.1 (S.D.=11.9) to 85.1 (S.D.=10.8) ($p=0.00001$) when MDT was used.

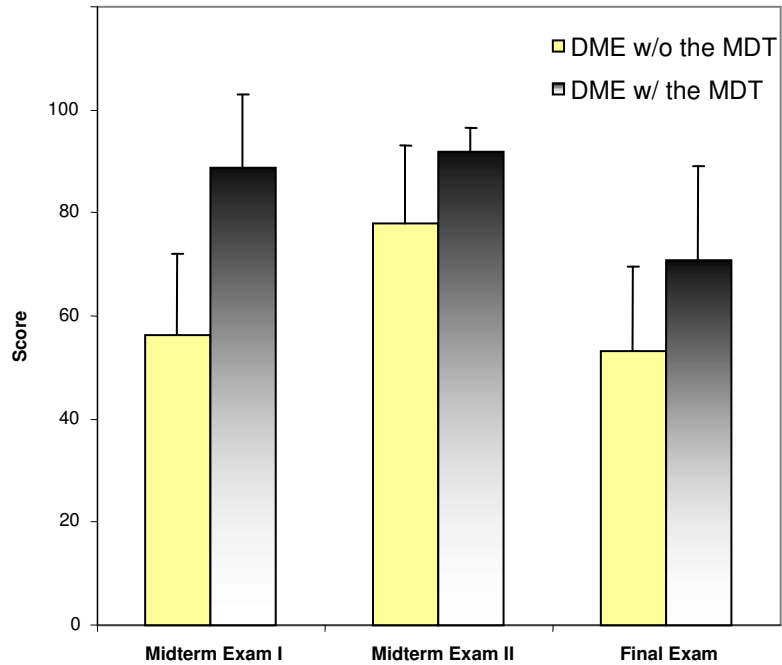


Figure 7 Comparison of exam scores from two separate semesters without and with the use of the MDT in the DME class. The exam scores were significantly different ($p < 0.00001$).

Conclusions

It is suggested that the use of computation tools in the format of MATLAB toolboxes would be effective in laboratory/discussion setting in conjunction with class demonstration.

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