Virtual Shoe Test Bed: A Computer-Aided Engineering Tool for Supporting Shoe Design

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ABSTRACT

This paper introduces an innovative Computer-Aided Engineering (CAE) system called Virtual Shoe Test Bed (VSTB) for supporting the development of new shoe designs. The proposed system includes functional design criteria for the different shoe elements in order to support the definition of the best solution for each product based on user needs and preferences. This is achieved by simulating physical tests which predict the interaction between shoe and user in order to obtain an estimation of several performance ratings without the necessity to manufacture and validate physical prototypes. The paper presents all functional criteria simulated in VSTB which provide a unique framework for supporting shoe design from the engineering point of view.

Keywords: shoe design, functional criteria, shoe performance rating, virtual experimentation.

1. INTRODUCTION

Recent advances in informatics lead to the development of CAD systems that are incorporated in the engineering design process. Analytical tools such as 2D and 3D drafting tools, stress analysis, etc., are used to design engineering products. Through the introduction of computers, robotics, CNC machines, flexible manufacturing systems (FMS) and nowadays, reconfigurable manufacturing systems (RMS) the degree of automation in the manufacturing processes is very high. In addition, artificial intelligence (AI) raises expectations for advancing CAD technology. New tools based on knowledge-based systems, fuzzy logic, artificial neural networks and genetic algorithms can enhance CAD systems. These tools lead to intelligent CAD systems (ICAD) and furthermore to intelligent computer-integrated manufacturing (ICIM) systems or intelligent manufacturing systems (IMS) [13].

According to Boer et al [5] footwear manufacturing has been evolved from craft production in the middle of 19th century to mass customization and personalization in the beginning of the 21st century where goods and services are more tailored to the specific needs and tastes of the consumers. According to these, the need for more intelligent Computer-Aided Design systems and simulators as well as complete manufacturing solutions is growing. Therefore, several efforts are being devoted nowadays in making shoe industry human-centered by developing new concepts for customizing or personalizing the final products [9-10].

The design and manufacture of a shoe includes the following phases [12], [14]:

- Creative design of the shoe.
- Industrial design of the shoe.
- Cutting of the leather.
- Stitching, assembly and finishing of the shoe.

This paper is focused on the first two phases of shoe design. In the first phase, a creative designer sketches the shoe. This is the process of conceptual design and is usually made on paper. However, in the recent years, CAD and VR tools are developed in order to support this process ([12], [14], [18]). In CAD systems, 3D digitizers are used to capture the geometry of existing lasts and store it in digital format. Then the designer can start a new design of a shoe in the system, making more trials and thereby exploiting better his creativity. VRShoe [18] is a virtual reality environment for designing shoe aesthetics which gives in the whole conceptual design process more immersion and interaction supporting the designer's work. Commercially available tools for digitization of last and conceptual design of shoe include amongst others the LastElf and the ImagineElf by Digital Evolution System [6], RhinoShoe by TDM Solutions [17], Shoemaker by Delcam [16] and RomansCAD by Lectra [15]. More tools are now available which can be used to accelerate concept design by eliminating tasks like reverse engineering and surfacing from the early design-phases of shoe [4], [11].

Industrial design involves the conversion of the concept into real product. This process is performed mostly by technicians who ensure the correct proportions and dimensions of the design and the easiness of manufacture. This phase includes the pattern-making of the design which is the conversion of the 3D upper of the shoe into 2D forms which will be cut in the following phase from a 2D leather ply. This process involves the flattening of the 3D design [2], [3], and the addition or removal of the material in order to be assembled in the 3D final product. The process of flattening using a CAD system is very quick comparing to the manual process and it is supported by almost all systems' developers.

Concluding, footwear industry is being modernized by using the technologies mentioned above to develop new shoe designs and collections from three up to six times per year. However, from the engineering point of view, no significant progress has been achieved so far towards supporting the design of new concepts of footwear in other aspects such as: rigid elements (heel/toe elements), flexible/soft elements (heel cushions, joint flexion elements) and 'sock' (or upper) elements (water and temperature regulating elements).

This paper introduces an innovative Computer-Aided Engineering (CAE) system for supporting the development of new shoe concepts. This system includes functional design criteria for the different shoe elements in order to support the definition of the best solution for each product based on user needs and preferences. This is achieved by simulating the behavior of shoe components and the interaction between shoe and user in order to provide a predictive estimation of the fitting, comfort and performance ratings without the necessity to manufacture and validate physical prototypes.

2. VSTB ARCHITECTURE

The main architecture of VSTB is depicted in Fig. 1. The system is intended for maximum usability and therefore input data can be generated from a CAD system ("CAD output") with the form of STL files representing the surface geometry of all shoe components. This data can be directly transferred into a "VSTB input file" or to the VSTB graphics environment ("GUI I/O"). In the latter case, the user has the opportunity to provide additional data in order to configure the underlying virtual tests. An intermediate "Shoe Shape Simplifier" (SSS or 3S) is invoked in order to prepare the necessary geometric data to perform the VSTB tests. The VSTB simulation processor executes the tests specified in the "VSTB input file" and reports the results in the "VSTB output file". The user is then able to see a visual interpretation of the results in the system's GUI or to import them in a "Third party's GUI" such as the GUI of a CAD system.

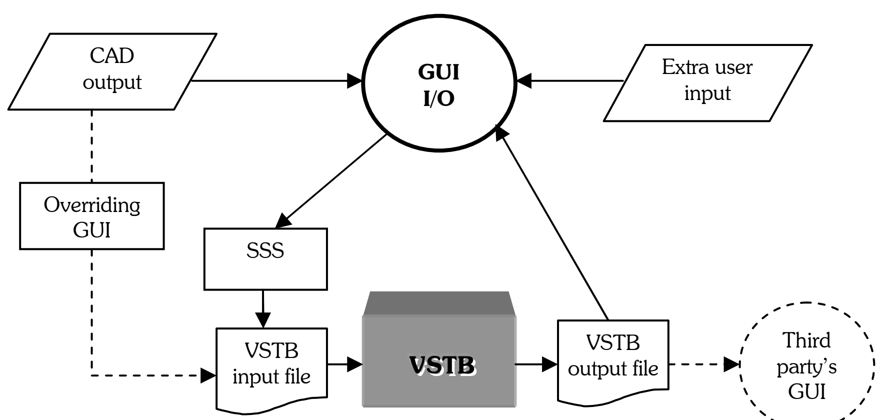


Fig.1: The main architecture of VSTB.

To facilitate data exchanging between a shoe CAD system and VSTB, both input and output files are xml-coded with fixed specifications. However, it is out of the scope of this paper to provide extensive information about the corresponding file formats.

The basic building blocks of the system are shown in Fig.2:

- *A converter from the CAD system to the VSTB simulation:* With this subsystem the user and/or the converter is associating shoe parts with materials properties and VSTB tests.
- *The VSTB simulation processor:* The core subsystem which computes shoe properties with respect to the underlying formulation of shock absorption, cushioning, bending/flexibility, torsion, stability, weight, thermal comfort and fitting.
- *Databases:* The "materials" database holds the necessary material properties related to the VSTB tests; The "anthropometric" database holds data values with respect to foot dimensions; The "limits" database holds boundary values of the evaluated properties related to typical use or typical user groups (children, elderly, men, women, …) of the shoe under evaluation.
- *Performance evaluator:* This subsystem is responsible for presenting the calculated values (scores) to the user according to the corresponding boundary limits.

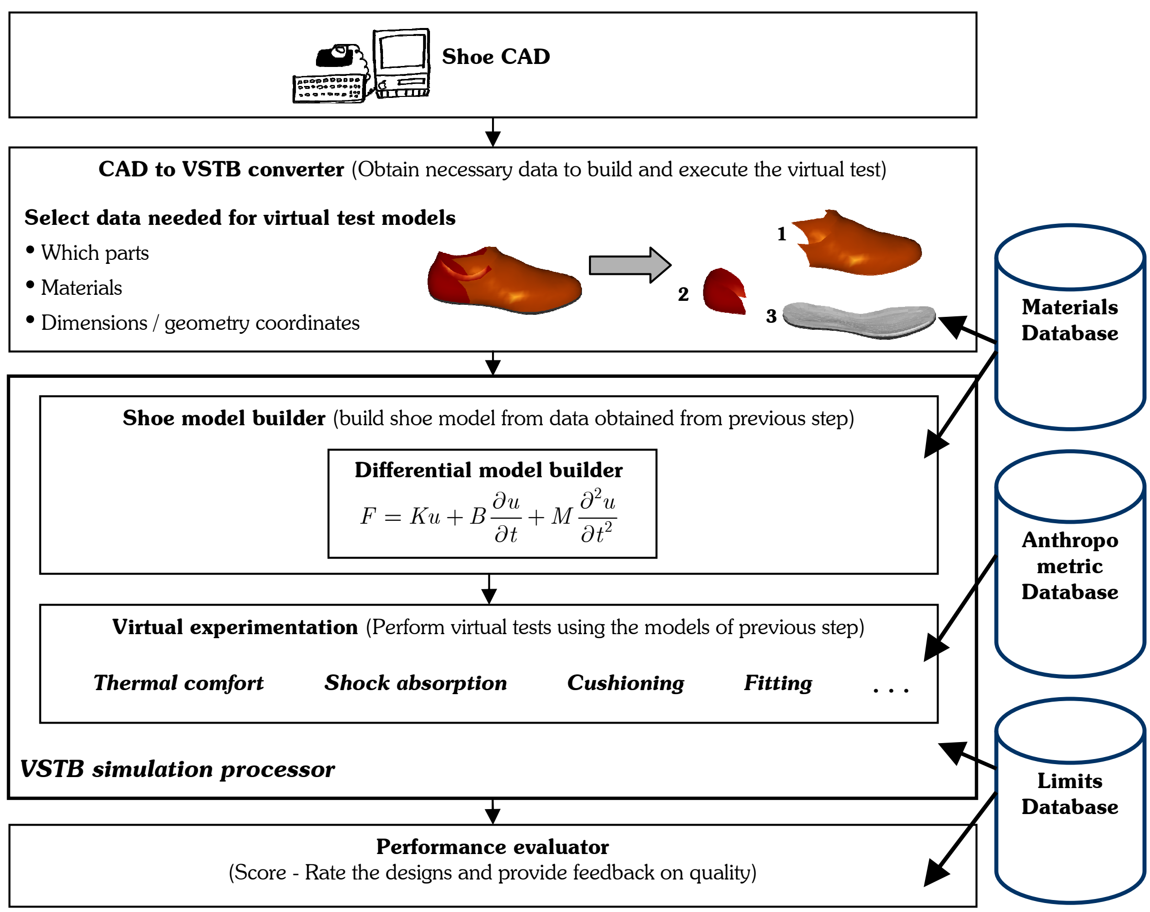


Fig. 2: The building blocks of the proposed VSTB simulation.

2.1 CAD to VSTB Converter

Shoe data are exported form the CAD system as a set of STL files. The converter processes shoe geometry and through Shoe Shape Simplifier the most essential/critical sizes/measures of the shoe are calculated. That data are passed to the VSTB core processor for performing the actual virtual tests. This simplification process is necessary in order to avoid employing a complete 3D shoe model along with a complex Finite Element Method in the VSTB core unit. Under this way it is possible to avoid developing an expensive tool that would work rather slow and would need quite some expertise from the user which is often not available in the shoe industry. It is therefore chosen to use a simplification which might be less accurate, but it is much quicker and less expensive.

2.2 VSTB Simulation Processor

The core subsystem of VSTB is responsible for two tasks: (a) Building an adequate differential model of the various shoe components and (b) executing the virtual tests selected by the user. A brief description of these tasks is given below.

2.2.1 Differential Shoe Model

In principle three modeling methods were considered for use in the VSTB:

- *DF: analytical differential equation of dynamic force equilibrium.* Predominantly one-dimensional analytical description which can be resolved using available numerical methods and/or toolkits.
- *MB: multibody models.* Multi-dimensional differential description modeled like a set of springs-dashpots and masses which allows for detailed contact interaction (geometry). No internal stresses / strains can be computed.
- *FE: finite element models.* A continuum is separated in a finite number of sub volumes. Stress equilibrium is computed for each volume. Detailed geometric description, internal stresses and strains can be computed.

Tab.1 lists all three modeling methods mentioned above along with their advantages and disadvantages with respect to the VSTB concept. Based on these remarks the current version of VSTB simulation processor is implemented using the DF model. The main idea is to start with a less complex modeling scheme and later improve only those tests which might work less accurately.

Model type	*Benefits*	*Drawbacks*
DF: differential model	Few material parameters required. Computationally fast. Easy pre-/post-processing. Easy to implement.	Very simplified, constant, simple geometry assumed. Limited validity range. Identification from certain (geometric) parameters from 3D CAD file is needed.
MB: multibody model	Medium number material parameters. Computationally fast. Easy pre-/post-processing (when made scalable).	Less simplified. Less model assumptions needed. More difficult to implement.
FE: finite element model	Realistic/accurate. Detailed contact interaction. Detailed stress – strain computation possible. Effect shape changes on global external forces can be determined. Many parameters can be varied.	Many parameters to identify Large computational effort. Automated tools required for pre-processing. External (commercial) code is required.

Tab. 1: The pros and cons of the three modeling methods taken into consideration for the VSTB tool.

Using DF model, the geometry of shoe elements is described mainly using one dimensional parameters expressing such entities as lengths, widths, heights and thicknesses. These parameters are combined with the corresponding material properties stored in the materials database and the entire data is substituted in the appropriate differential equation according to the test which is performed.

2.2.2 Differential Shoe Model Solver (Virtual Experimentation)

In this step the real calculations of the shoe properties are performed taking into account the final differential equation(s) derived at the previous step. The solver uses boundary conditions stored in the limits database and applies the appropriate numerical method to obtain the final data consisting of reaction forces, motions, etc.

2.3 Performance Evaluator

In this block of the VSTB tool, the calculated output of the simulation processor is compared to the limit values that are defined for the specific shoe and its intended usage. Appropriate data are selected from the materials and limits database in order to calculate the performance rating (score) of the virtual tests that have been performed. These scores are displayed to the user using a graphical interface in order to provide a fast and comprehensive visual impression of the performance of the evaluated shoe. As an example, such a graphical interface is given in Fig. 3.

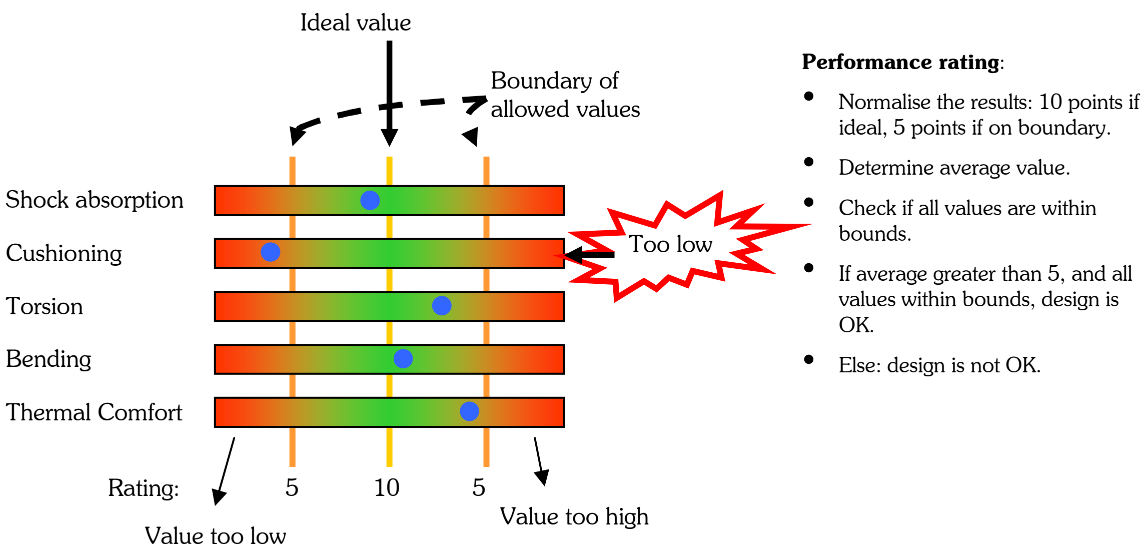


Fig. 3: The graphical interface for presenting the VSTB results to the user.

The output information of every virtual test is a score bar with two limits which define the suitable range to obtain an adequate behavior. The score obtained for each functional aspect is a weighted value calculated from the parameters estimated with each prediction model. For example, the output parameters for the shock absorption model are energy absorption and rigidity. Therefore the corresponding shock-absorption score is a weighted combination of these two parameters.

3. VSTB TESTS

n this section we provide the main principles of the various VSTB tests. A complete description of each test is considered to be out of the scope of this paper.

3.1 Shock Absorption

The shock absorption test simulates the behavior of shoe materials in the first phase of walking, when heel contacts the ground. In this phase a significant impact force is transmitted from the heel through all the body joints which could be damaging under repeated cycles. In lab environment this is simulated as a drop test carried out with physical prototypes. The vertical displacement and the energy dissipation are measured to evaluate the shock absorption property of the shoe [7]. In VSTB, shock absorption is simulated using the parts of the shoe which correspond to sole, mounting insole and insole. The DF model requires the thickness of each component and material properties like, for example, the coefficients of rigidity and viscoelasticity.

The corresponding mathematical DF model has been obtained after performing several tests with real and simulated materials and comparing the results. In this way, a general DF model has been developed to be further fine-tuned in order to particularize the behavior of each material. This DF equation relates the mechanical stiffness σ and strain ε (time function curves) by means of eight coefficients for each material. The final behavior is obtained combining the model of all the materials of the bottom part of the shoe.

$$\sigma = a + b \cdot \varepsilon_i^{\,c} + d \cdot \varepsilon_i^{\,e} \cdot \dot{\varepsilon}_i^{\,f} \cdot \left|\dot{\varepsilon}_i\right|^{g} - h\dot{\sigma} \qquad (3.1)$$

$$\varepsilon = \sum \varepsilon_i \tag{3.2}$$

The resulting output of this test consists of the following parameters:

- *Energy absorption:* Capacity for absorbing energy during deformation.
- *Maximum deformation*: Maximum level of compression of the sole materials under load.
- *Rebound:* Residual displacement between two consecutive steps.
- *Dynamic stiffness:* Expresses the necessary force required to compress the material.
- *Dissipated energy ratio:* Represents the capacity of the material for dissipating the shock energy.

3.2 Cushioning

This test simulates the capacity of the material for distributing in an adequate way the pressures: (a) under the heel, first metatarsal head and first toe (high pressures), and (b) on the footplant (low pressures). In lab environment this test is carried out with physical prototypes and a universal test machine which allows introducing specific pressure – time loads carrying out a displacement control [1]. In VSTB, cushioning is simulated using the parts of the shoe which correspond to sole, mounting insole and insole. The DF model requires the thickness of each component and material properties like, for example, the coefficients of rigidity and viscoelasticity. The corresponding mathematical DF model has been obtained according to the strategy described in section 3.1, while the resulting output consists of the parameters described therein.

3.3 Torsion

The torsion test simulates the behavior of the shoe when it is revolved around its main (length) axis. In this test, the heel of a shoe prototype is usually fixed in a certain position and with the aid of lab equipment the forepart is rotated at predefined angles. In VSTB torsion is simulated using the various parts of the sole (forepart, midsole, heel, etc.). The DF model requires sole width, the thickness of each sole component and the corresponding material coefficients of rigidity.

The mechanical torsional behavior of the shoe is modeled as a set of torsion springs and dashpots in series and parallel. The torsion behavior for each geometrical and material part can be seen like a mechanical spring element with torsion stiffness $k_{i,j}$, where i denotes the part number and j the corresponding material. The resulting output of this test is a global *torsion stiffness coefficient* K_t.

3.4 Thermal Comfort

The thermal comfort test simulates Thermal Transmission which allows obtaining the thermal resistance and the water vapor transmission of the footwear. These parameters are related with the temperature and humidity inside the shoe and in consequence with the thermal comfort. In lab environment, an impermeable sock that allows water vapor transport is introduced into the shoe. The sock is full of water at control temperature of 35ºC. The energy needed to maintain the water at the constant temperature of 35º is measured.

In VSTB, thermal comfort is simulated using all shoe parts. The DF model requires the thickness of each part, the percentage of the shoe surface covered by each material and the number of different shoe layers. The material properties required in this test include thermal and water-vapor resistance, absorption, wicking (water transmission coefficient through materials).

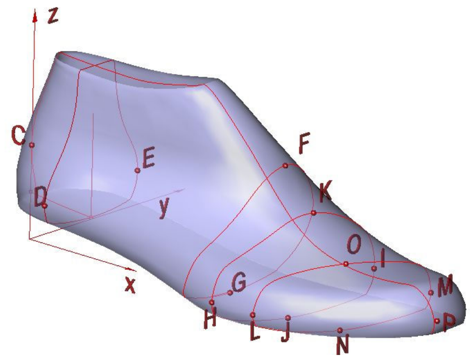
The corresponding mathematical DF model consists of two prediction modules. The first one estimates the whole shoe thermal characteristics, while the second model evaluates the shoe thermal comfort perceived by the user [8]. The resulting output of this test consists of the following parameters:

- Thermal resistance of the whole shoe.
- Water-vapor resistance of the whole shoe.

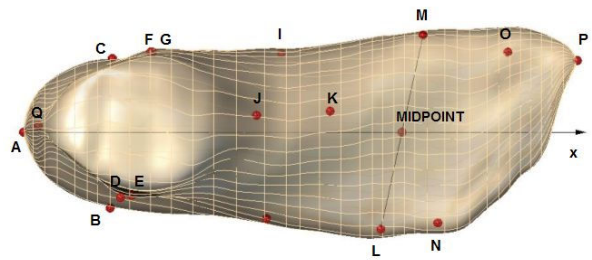
3.5 Fitting

The fitting test simulates the fitting of the foot inside a shoe. The test assumes that the last has same 3D shape with the inside of the shoe. Under this way a set of measurement is performed in the shoe last and it is compared with corresponding measurements stored in the anthropometric database. Under this way it is possible to predict inaccuracies in shoe fitting that will make the shoe user feel discomfort or pain.

In VSTB, the set of measurements is calculated using the 3D surface of the shoe last (see Fig. 4a). This calculation is achieved by identifying key-points on the last surface and computing the appropriate (geodesic) distances between them. Similarly, the anthropometric database contains several measurements which correspond to anatomical points of the foot (see Fig. 4b).



(a)



(b)

Fig. 4: (a) Key-points and length measurements on the surface of a shoe last. (b) Anatomical points of the foot.

3.6 Weight

The weight test is used to estimate the real weight of a virtual shoe in VSTB. The test is implemented using the volume V_i and the material density d_i of every shoe part. The mass calculation is straightforward, i.e., $m = \sum_i d_i V_i$.

3.7 Bending

The bending test simulates the bending behavior of the sole. During walking, shoe bending occurs in the region of the ball of the foot. Therefore bending is approximated as if the sole is fixed in this region. This approximation makes it possible to simulate the sole as a cantilever beam construction with fixation in the region of the ball of the foot and the (vertical) force applied in the heel redoing. Under this way it is also possible to validate this simulation in a laboratory set-up. In the VSTB bending test, the outsole, insole and mounting insole are of influence. The test accounts for different layers of these sole parts and their thicknesses. Furthermore, the DF model requires sole width, and material coefficients of rigidity.

The output of the test is determined as the first order coefficient of the fit through the bending moment versus the bending angle at predefined angles.

4. THE VSTB APPLICATION

VSTB is implemented in MATLAB as a standalone application. Significant effort has been devoted in making the application friendly to the end-user in the Footwear Industry. The main GUI is depicted in Fig. 5. The application is divided into several windows including:

- The 3D graphics window for displaying the 3D surface of the shoe and its last. This window is also used for making parts selection and assigning materials to the various pieces of the footwear.
- The Shoe Components pane for displaying the main structure of the shoe along with its various parts which are linked to the corresponding STL files.
- The Appearance and Properties pane, for displaying information related to the shoe, its intended usage environment, and for controlling the display of the various parts.

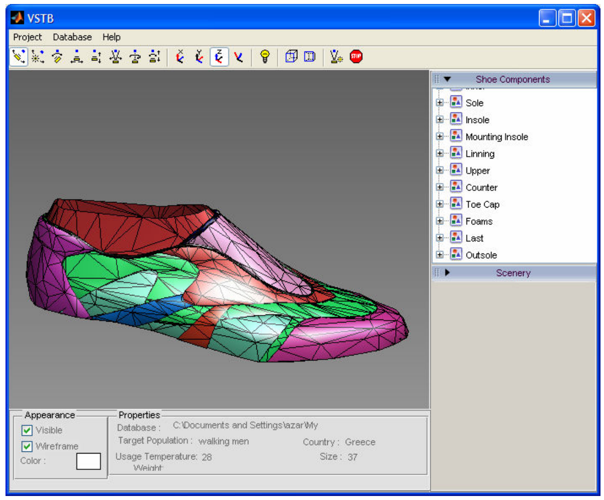


Fig. 5: The main GUI of VSTB application.

The entire application is controlled through a dialog interface called as "VSTB Wizard" which is responsible for collecting the necessary information for defining the shoe structure, assigning materials to shoe parts, and selecting and configuring the VSTB tests. Fig. 6 shows a few indicative steps of this procedure. Virtual experimentation is completed in seven sequential steps of the VSTB wizard.

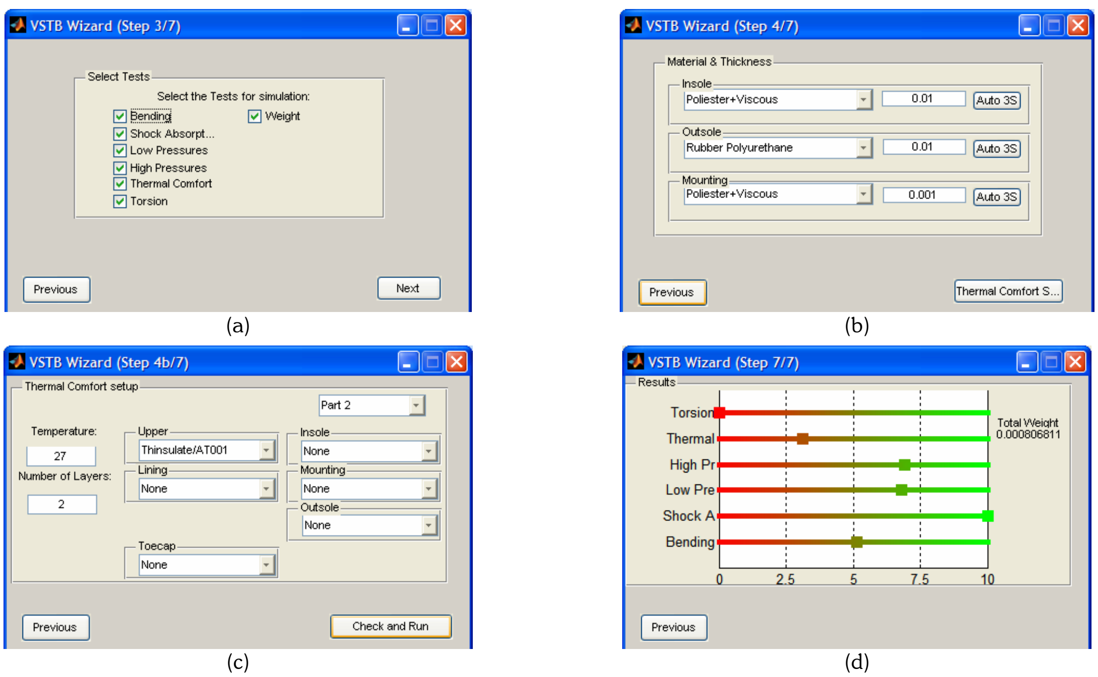


Fig. 6: A few indicative steps of running the VSTB application through the VSTB Wizard. (a) Selecting of VSTB tests to perform. (b),(c) Selecting materials for the appropriate shoe parts. (d) Displaying the results to the end-user.

Currently the VSTB application is under validation with the aid of footwear companies involved in this research. Individual tests have been checked by comparing the simulation results with the results of real tests carried out in lab. At this point the validation results are quite promising since the simulation and lab results match closely. Fig. 7 shows the validation results of the cushioning test where four sandwiches were build combining four different materials in a wide range of mechanical properties.

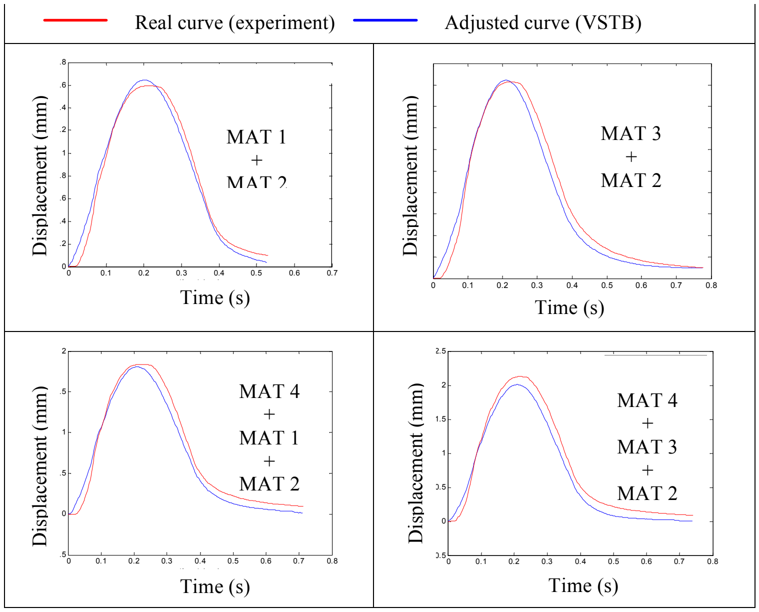


Fig. 7: Results of the validation of the cushioning test with different combination of materials.

Formulating the thermal comfort test is a more complex process since several shoe components are involved in the prediction model, while manufacturing variables have a significant influence (i.e., glue applications impose further heterogeneity in the shoe upper). The developed DF model for the thermal comfort test has been tested against twenty-five different shoe models the simulation results are very close to the real ones. Fig. 8 depicts the results of water-vapor resistance (Re).

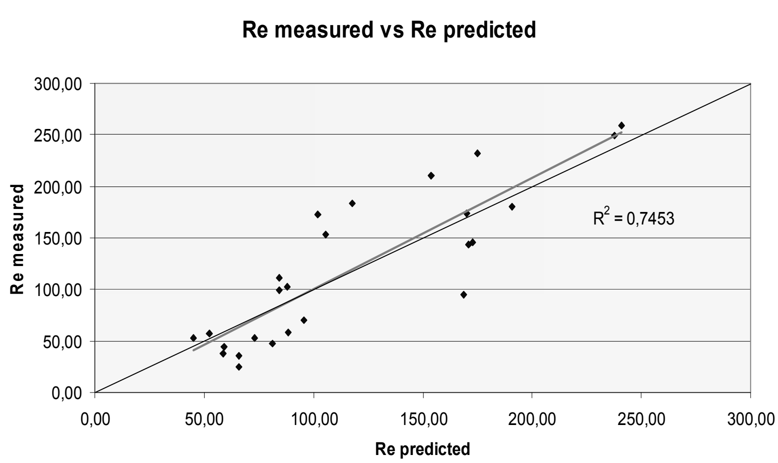


Fig. 8: Correlation between the measured and predicted values of the water-vapor resistance (Re) for 25 shoe samples.

Finally, all VSTB tests currently run in PC with a Pentium M-1.86GHz and 1GB memory in less than a minute.

5. CONCLUSIONS

A new computer-aided engineering tool has been proposed in this paper for supporting the development of new shoe concepts. This tool called as VSTB is simulating the main functional criteria which affect the performance of a shoe with respect to its interaction with the user. Virtual experimentation is achieved using a set of simulation tests which require a small amount of data from the system's user (shoe designer). The VSTB tool aims at providing footwear industry with new means of designing and engineering shoes without the need to perform excessive physical prototypes testing.

The overall system architecture is independent of any specific CAD system (commercial, freeware or research) since the VSTB simulation processor can be accesses through a set of specific xml-coded input/output files. Currently, the overall system is under validation by certain footwear manufacturers, while individual tools have been validated using conventional laboratory setups. The present implementation does not support specific types of shoes like boots, athletic, high-heel, etc., but it is rather focused on mainstream casual footwear. Significant efforts are currently devoted in introducing into the materials database the majority of materials used in footwear industry. Future research will concentrate on improving the simulation accuracy and the available range of shoes that can be tested in VSTB.

6. ACKNOLEDGEMENTS

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