An innovative virtual-engineering system for supporting integrated footwear design

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Abstract: This paper presents a new virtual-engineering platform, called as virtual shoe test bed (VSTB), for supporting the design of footwear from the engineering point of view. The proposed VSTB system includes various functional design criteria in order to support the definition of the best solution for each product utilising scenarios based on user needs and preferences. Using the proposed virtual-engineering system a designer is able to simulate the behaviour of footwear components and the interaction between shoe and user in order to derive a predictive estimation of the fitting, thermal comfort and performance ratings without the necessity to manufacture and validate physical prototypes. The present paper describes the architecture, the tests implemented in the final system along with corresponding lab experiments conducted in terms of industrial validation. All results and hints for future research are reported and discussed.

Keywords: shoe design; functional criteria; shoe performance rating; simulation; integrated design; virtual engineering platform.

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1 Introduction

During the last decade significant efforts have been devoted to transform the footwear industry from a labour-intensive activity to a knowledge-based manufacturing process. Modernising this so called 'traditional industry' does not mean to concentrate only on the Style and Design phase but it also means to be able to master the whole product and process life cycle adding value (knowledge and intangible) to each phase of shoe life-cycle. In order to achieve this goal, important innovations in engineering, informatics, materials, information and communication technologies, etc., are developed and adopted by this industrial sector (CEC, 2009; Chituc et al., 2008; Wong et al., 2006).

According to Zeid (1991) recent advances in the development of CAD tools and systems allow their incorporation in the engineering design process. Analytical tools such as 2D and 3D drafting tools (Piegl and Tiller, 1997), conceptual design tools (Robertson and Radcliffe, 2009; Sapidis et al., 2005), stress analysis tools (ANSYS, 2009), reverse engineering tools (Várady et al., 1997; Ye et al., 2008), etc., are utilised to design engineering products. Through the introduction of computers, robotics, CNC machines, flexible manufacturing systems (FMS) and nowadays, reconfigurable manufacturing systems (RMS) the current degree of automation in the manufacturing processes is very high (Jimeno et al., 2006; Hu et al., 2007; Koren et al., 1999). 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 (Yang and Lin, 2009; Crispin et al., 2005; Wang et al., 2003). According to Kopacek (1999) these tools lead to intelligent CAD systems (ICAD) and furthermore to intelligent computer-integrated manufacturing (ICIM) systems or intelligent manufacturing systems (IMS).

On the other hand, according to Boer et al. (2004) footwear manufacturing has evolved from craft production in the middle of 19th century to mass customisation and personalisation 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 CAD systems and simulators as well as complete manufacturing solutions is growing. Therefore, several efforts are being devoted nowadays in making shoe industry human-centred by developing new concepts for customising or personalising the final products (Lee, 2006; Leng and Du, 2006; Luximon et al., 2003).

Apparel industry and in particular textile and clothing, has made steps towards supporting product design from the engineering point of view (Wang and Yuen, 2005; Choi and Ko, 2005; Wang et al., 2005). According to Mao et al. (2008), an innovative method consisting of a CAD system, allowing the designer to perform multi-style clothing thermal functional design on a customised virtual human body is presented. Although shoes are taken into account the system is not able to provide analytical data for assessing the quality of a certain shoe design with respect to its thermal comfort parameters. Today, not only can clothing be simulated and animated with remarkable realism, but also speed and quality are being improved by developing or refining models and algorithms (Breen et al., 1994; Volino et al., 1995; Eberhardt et al., 1996; Baraff and WitKin, 1998; Choi and Ko, 2002; Cordier et al., 2003; Fontana et al., 2005). However, these pioneer achievements are mainly focused on the mechanical behaviour of textile and clothing.

The purpose of this paper is to introduce an innovative virtual engineering system for supporting the development of new shoe concepts from the engineering point of view.

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 the behaviour 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.

The rest of this paper is structured as follows. It begins with a state of the art survey concerning methodologies and software tools that are used to aid the designers during the early stages of shoe design in Section 2. Sections 3 and 4 continue with an analysis of the system architecture of the proposed system and the presentation of the supported virtual tests. The developed virtual-engineering application is presented in Section 5 and some industrial tests and validation results are presented in Section 6. Finally concluding remarks are closing this paper.

2 Previous work

The design and manufacture of a shoe includes the following main phases (Mermet and Roche, 1982; Paris and Handley, 2004):

- 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 (Ye et al., 2008; Robertson and Radcliffe, 2009; Mermet and Roche, 1982; Paris and Handley, 2004; Vigano et al., 2004). In CAD systems, 3D digitisers 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, making more trials and thereby exploiting better his creativity. VRShoe (Vigano et al., 2004) 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 digitisation of last and conceptual design of shoe include amongst others the LastElf and the ImagineElf by Digital Evolution System (DES, 2009), RhinoShoe by TDM Solutions (TDM, 2009), Shoemaker by Delcam (Shoemaker, 2009), RomansCAD by Lectra (RomansCAD, 2009) and ShoeMaster by CSM3D (ShoeMaster, 2009).

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 (Azariadis and Aspragathos, 2001; Azariadis and Sapidis, 2004) and the addition or removal of the material in order to be assembled in the 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 current systems.

The development of new design tools for sole (Kim et al., 2008) or upper (Jing et al., 2005) parts allow the addition of very small details in the shoe design process. In addition, new digital design paradigms support direct style-lines development and allow shortening of the conceptual-design cycle (Azariadis and Sapidis, 2004, 2005; Liu et al., 2006).

From the engineering point of view, a virtual CAD system named ‘P-smart’ has been developed by Yi et al. (2006) for designing cloths taking into account thermal functional properties. The proposed system enables the user in a virtual environment to design the clothing with wearing scenarios and preview its thermal performance throughout certain simulated scenarios. Through this system a framework of computational engineering design for thermal functional performance of clothing, particularly for designing multi-layer garments (Wang et al., 2006), has been developed. Later, Mao et al. (2008) proposed a new CAD system called as ‘T-smart’ that allows the designer to carry out thermal functional design considering the effect of different clothing styles. Using this new system, the designer can investigate the effects of using different materials and styles for different body parts (i.e., hats, underwear, jackets, trousers, gloves, socks, etc.) by simulating and previewing the thermal performance of clothing during different wearing scenarios. Although, in principle this system is able to consider shoe data it is not possible to provide analytical results on the thermal comfort related to footwear. On the other hand, compared to the traditional clothing design method, these new design methodologies show many advantages, such as shortening the design cycle and avoiding unrealistic physical trials.

Taking the above into account, it is concluded that no significant progress has been achieved so far towards supporting the footwear design from the engineering point of view. The purpose of this paper is to introduce a new virtual engineering system called as ‘virtual shoe test bed or VSTB’ which incorporates tools and methods for calculating the influence of various elements in the overall shoe performance. Such elements include: rigid elements (heel/toe), flexible/soft elements (heel cushions, joint flexion elements) and upper elements (water and temperature regulating elements). Using the proposed VSTB system a designer is able to determine 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 behaviour 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.

The main system architecture and modules have been introduced in Azariadis et al. (2007) using a preliminary version of the proposed tool. In this paper, we focus on the presentation of the final set of virtual tests supported by the proposed system, giving emphasis on the underneath mechanical concepts utilised for that purpose. We also present new results derived by our industrial experiments with real shoes and materials.

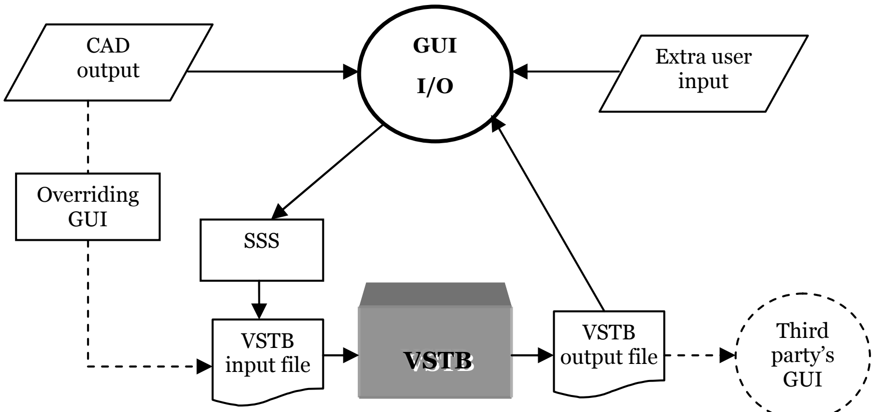
3 System architecture

The main architecture of VSTB is depicted in Figure 1. The heart of the system is the ‘VSTB Kernel’ which is responsible for performing all necessary calculations. The

VSTB Kernel is accessed through a 'VSTB input file' which holds all information related to the geometry and materials' properties of the shoe model that is under testing control. The results of the underlying calculations are written to a corresponding 'VSTB output' file. The system utilises a GUI interface in order to prepare CAD shoe data (usually STL files) for testing. This procedure includes the separation or collection of STL files into logical shoe parts and the assignment of the corresponding materials. The system invokes an intermediate module called as 'shoe shape simplifier (SSS or 3S)' in order to simplify the 3D geometry according to the simulation model used in every virtual test.

The system is able to work by overriding the Graphical User Interface since data exchanging between a shoe CAD system and VSTB can be achieved through the corresponding input/output files which are xml-coded with fixed specifications.

Figure 1 The main architecture of VSTB



The basic building blocks of the final system include:

- *CAD-to-VSTB converter:* It is used to define logical shoe parts with associated materials from CAD files.
- *The VSTB simulation processor:* The core subsystem which computes the performance of various shoe properties. This subsystem includes various differential models (DF) used for performing the required virtual tests (Azariadis et al., 2007).
- *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 properties values (scores) according to the corresponding boundary limits.

The interested reader is referred to Azariadis et al. (2007) for an extensive presentation of all the above components. The rest of this paper is focused on the underneath mechanical concepts utilised in the various virtual tests.

4 Virtual experimentation

The VSTB aims at supporting a variety of tests which include the following shoe properties:

- shock absorption
- metatarsus pressure
- heel pressure
- bending
- torsion
- thermal comfort
- stability
- fitting
- friction
- weight.

The purpose of the above mentioned properties is not limited to providing a performance of the shoe itself, but reflects the physical interaction between the user and the shoe, and, as such, they are called as *functional properties*. These functional properties are important to determine the usability of the shoe for the intended use, and are normally measured in so-called biomechanical user-tests; with people walking with footwear. The VSTB, therefore, provides an estimation of the usability of the shoe, with respect to the target group where the shoe is aimed for and with respect to the use for which the shoe is intended to.

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

4.1 Shock absorption

The shock absorption test simulates the behaviour 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 to all body joints. This force propagation could be damaging under repeated cycles. In lab environment, this test is reproduced as a drop test carried out with physical prototypes. The shock absorption property of the shoe is evaluated by measuring the vertical displacement and the energy dissipation (García et al., 1994; Alcántara et al., 2001). In VSTB, shock absorption is simulated using the parts of the shoe which correspond to outsole, mounting insole and insole (in the following sections, it will be referred as *sole* for brief).

The resulting output of this test consists of the following mechanical 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.

4.2 Heel pressure

The heel pressure-distribution test measures the capacity of the footwear to distribute the pressure under the heel during the first half of the stance phase in the gait cycle, when the heel strikes the ground. During this moment, all body weight and its inertia have to be received by the heel and transferred to the forward part of the foot in order to facilitate propulsion. In order to increase comfort, during this sub-phase of the gait cycle, high-pressure points should be eliminated (Brown et al., 1996) by allowing at the same time forward load transference for gait efficiency (Nawoczenski et al., 1995).

This test is simulated by following the same approach with shock absorption: the sole components are considered with their geometric characteristics (e.g., thicknesses), while material properties (e.g., capacity to deform under a predefined load).

The following mechanical parameters are extracted from this test:

- *Maximum deformation:* maximum level of compression of the materials of the sole under load.
- *Energy absorption:* capacity of absorbing pressure energy during materials deformation.

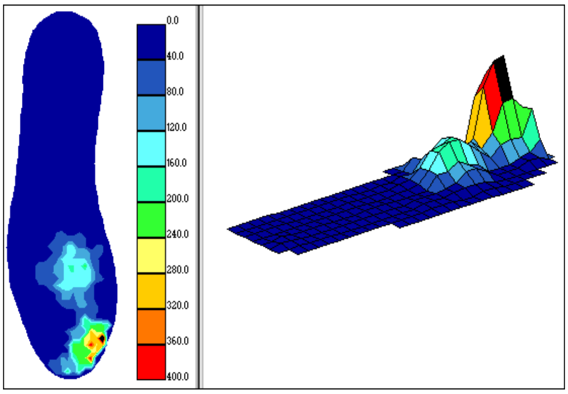
4.3 Metatarsus pressure

This test analyses the capacity of the sole materials to distribute in an adequate way the pressures under the metatarsal heads. During the last half of the stance phase in gait cycle, just after the heel takes off the ground, forward propulsion is needed in order for the body to advance. At this moment all the pressure is placed under the metatarsal heads, which are used to push the body weight forwards (see also Figure 2). An increased pressure can produce discomfort and even, if disease is present, blisters and wounds (Gefen, 2003).

Similarly to the aforementioned cases of shock absorption and heel pressure, the simulation of the metatarsal-pressure test considers that the bottom part of the shoe consists of the sole components. The same approach has been applied to combine the materials of the different components, which results in a force-deformation curve as output. After processing, the following mechanical parameters are derived:

- *Maximum deformation:* maximum level of compression of the sole materials.
- *Energy absorption:* capacity of absorbing energy during the deformation.

Figure 2 Example of metatarsus pressure distribution during the push off (see online version for colours)



4.4 Bending

The bending test simulates the bending behaviour of the sole. During walking, shoe bending occurs in the region of the ball of the foot and it 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. In the VSTB, the test accounts for different layers of the 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.

4.5 Torsion

The torsion test simulates the behaviour 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 and the DF model requires sole width, the thickness of each sole component and the corresponding material coefficients of rigidity.

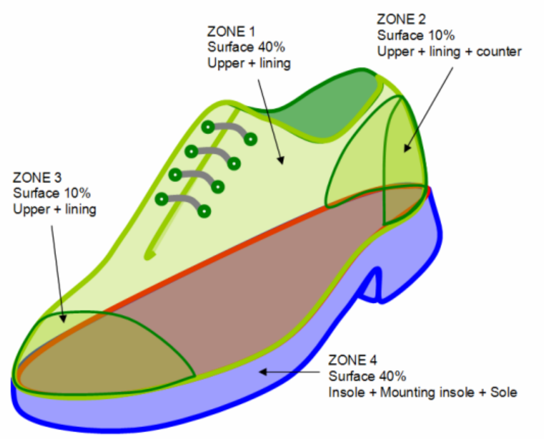
The mechanical torsional behaviour of the shoe is modelled as a set of torsion springs and dashpots in series and parallel. The torsion behaviour for each geometrical and material part can be seen like a mechanical spring element with torsion stiffness $k_{i,j}$, where *i* denotes the part number and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

4.6 Thermal comfort

Thermal comfort is related with the temperature and humidity inside the shoe. This test simulates mass and thermal transmission between foot and environment, which allows quantifying the interaction between the footwear and its users with respect to thermal and sweating parameters (González, 2007; González et al., 2001). 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 vapour transport is introduced into the shoe. The sock is full of water at control temperature of 35°C. The energy needed to maintain the water at the constant temperature of 35° is measured. Both measures allow quantifying the thermal transmission and the water vapour transmission resistance of the whole footwear.

In VSTB, thermal comfort is simulated using all shoe parts separated into four zones, as it is shown in Figure 3. For each zone, the implemented DF model requires its surface area, the number of different layers which consists of, and the material and thickness of these layers. The properties required for each material include the thermal resistance and the water-vapour transmission resistance.

Figure 3 Example of different zones and layers for a casual footwear (see online version for colours)



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

- *thermal resistance* of the whole shoe
- *water-vapour resistance* of the whole shoe.

4.7 Stability

The stability test evaluates the behaviour of the shoe when misplacing the foot on an object or slope or, when induced by a misstep, placing the foot 'skewed' with respect to the floor. The consequence of a skewed placement of the foot, results in a moment around the ankle. Stability, therefore, can be split into *ankle stability* and *shoe stability*. For the VSTB only shoe stability has been taken into account.

The definition of stability in the VSTB is derived from Archimedes definition of *ship stability*. In that definition, stability is being represented by a metacentric height. Tilt occurs when the vertical force passes the tilt line.

In lab environment, stability is evaluated with physical prototypes on a tensile testing machine combined with a horizontal board displacement. The vertical displacement, vertical force and horizontal displacement are measured and the metacentric height is then determined.

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

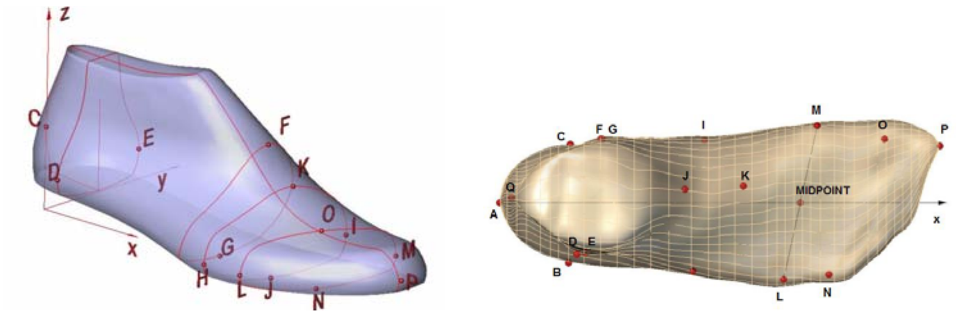
- *Deformation:* level of deformation of the shoe sole material in the skewed position.
- *Metacentric height:* residual displacement between non-deformed material and deformed material in the skewed position. Indication of stability level.

4.8 Fitting

The fitting test allows quantifying the fitting of the foot inside a shoe. The test assumes that the inner 3D geometry of a shoe is the same with the 3D shape of the corresponding last. A set of measurements are taken from the shoe last and the results are compared with the corresponding measurements stored in an anthropometric database, which represents the *target population*, e.g., men, adults, size 42. This allows predicting inaccuracies in shoe fitting that will make the shoe user feel discomfort or pain (Olaso et al., 2007).

With VSTB, the set of measurements are derived using the 3D surface of the shoe last [Figure 4(a)]. 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 for different kinds of populations [Figure 4(b)].

Figure 4 (a) Key-points and length measurements on the surface of a shoe last (b) anatomical points of the foot (see online version for colours)



(a) (b)

For the needs of comparing a foot against a shoe last the following parameters are extracted (w.r.t. Figure 4):

- *Functional length:* distance from point **C** to **P**, measured on the last surface (passing through the bottom of the last).
- *Rearfoot width:* distance from point **D** to **E** (passing through the bottom of the last).
- *Instep perimeter:* perimeter of the last section passing though point **F**.
- *Metatarsal perimeter:* perimeter of the last section passing though points **H**, **K** and **I**.
- *Toes width:* perimeter of the last section passing though points **L**, **O** and **M**.

4.9 Friction

Friction is a very important parameter with respect to footwear functionality. Studies in this field are mainly concentrated on the behaviour of the sole polymer under different friction and wear conditions. For example, it is known that friction behaviour of polymeric surfaces depends on the applied load (Zhang, 1998; Myshkin et al., 2005; Bistac et al., 2006), the sliding velocity (Shooter and Thomas, 1952; Flom and Porile, 1955a, 1955b; White, 1956; Milz and Sargent, 1955; Tanaka, 1984; Fort, 1962; Vinogradov et al., 1970; Heiden et al., 2006), the material physical characteristics, such as hardness and shear strength (Gorb et al., 2002; Ludema and Tabor, 1966; King and Tabor, 1953) and temperature (Strandberg, 1985; Vinogradov et al., 1970; Shooter and Thomas, 1952; Ludema and Tabor, 1966; King and Tabor, 1953). Despite all these studies, the dynamics between friction and these parameters are not clear. For example, the proportionality of friction and load only exists in a controlled range of conditions. Similar situations can be found with other parameters. In fact, the non-linear nature of the friction caused by the complex contribution of each parameter to the frictional properties, in addition to the great diversity of external factors (i.e., surface contaminants, temperature, surface irregularity, etc.), makes it very difficult to develop a mathematical model of the friction between shoe sole and the ground floor.

However, since friction is perceived as an important footwear property, an alternative approach was applied to include the friction test in the VSTB: based on previous knowledge (e.g., Li and Chen, 2004; Chang, 1998; Manning and Jones, 2001), a set of key questions were defined in order to allow a qualitative assessment of the friction properties of a sole. These questions refer to, for example, the area of braking, the area of propulsion, the design and placement of the studs, and so on. All these questions are combined through a weighed sum to provide a qualitative assessment of the level of friction provided by the sole.

4.10 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., $m = \sum_i d_i V_i$.

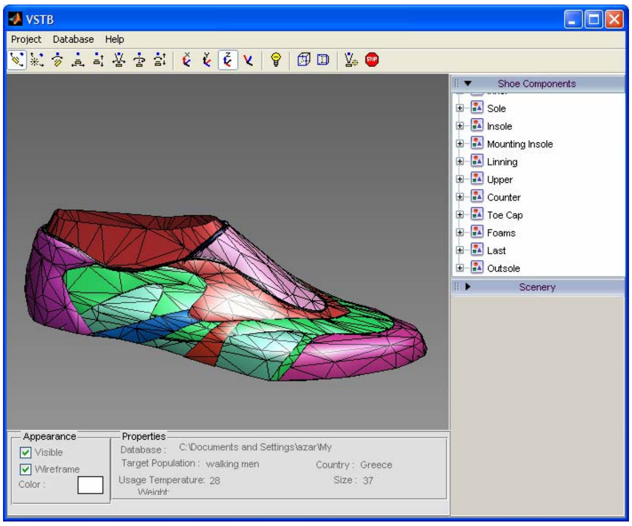
5 The final virtual-engineering application

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 Figure 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.

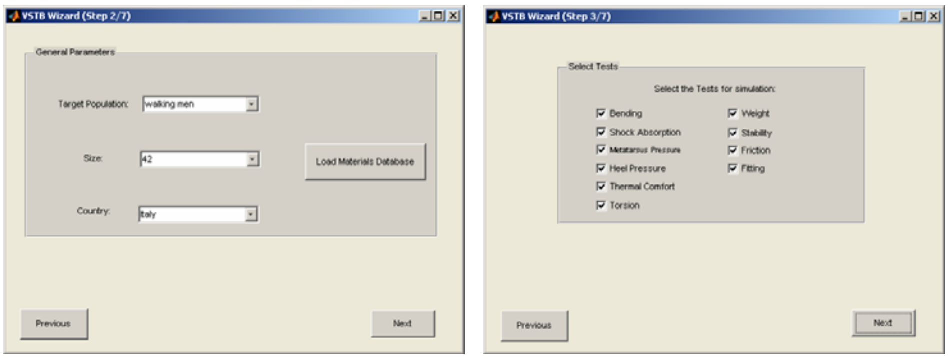
- The Shoe Components pane for displaying the main structure of the shoe along with its various parts which are linked to the corresponding STL files.
- The Appearance and Properties pane, for displaying information related to the shoe, its intended usage environment and for controlling the display of the various parts.

Figure 5 The main GUI of VSTB application (see online version for colours)



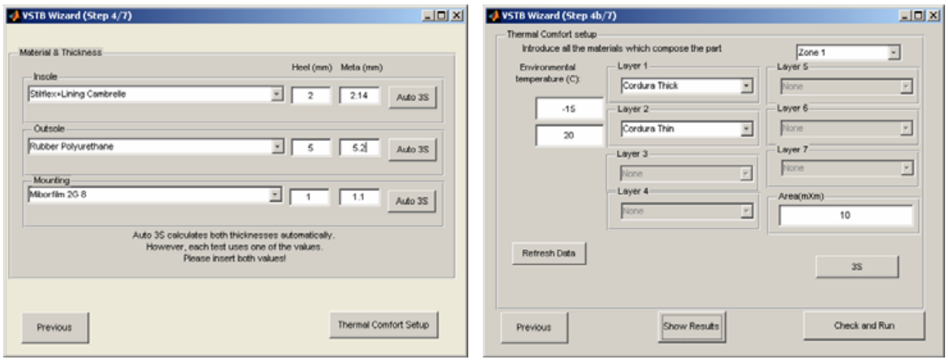
The entire application is controlled through a dialogue interface called as 'VSTB Wizard' which is responsible for collecting the necessary information for defining the shoe structure, assigning materials to shoe parts and selecting and configuring the VSTB tests. Virtual experimentation is completed in seven sequential steps of the VSTB wizard.

Figure 6 Selecting (a) demographic data and materials database (b) tests for simulation (see online version for colours)



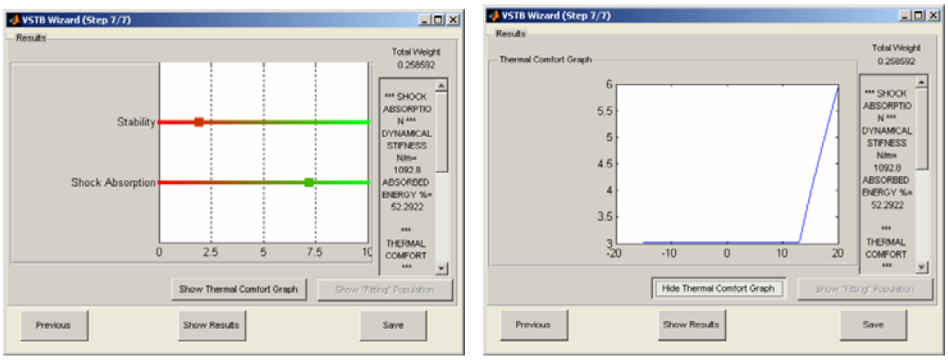
(a) (b)

Figure 7 (a) Material and thickness selection for tests (b) material selection, environment temperature bound and area calculation for thermal comfort (see online version for colours)

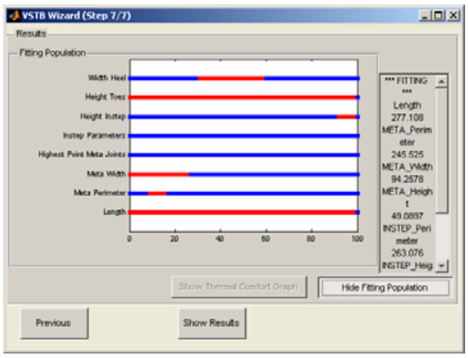


(a) (b)

Figure 8 Results presentation according to the test, weight is shown in all windows (a) score presentation for bending, shock absorption, metatarsus and heel pressures, stability and friction (b) graph presentation for thermal comfort (c) percentages of fitting with respect to the target population (see online version for colours)



(a) (b)



(c)

In the first step, the STL files containing the geometrical information of the shoe parts are inserted to the system. In the second step, the user enters demographic information and selects the appropriate materials database, a structured file that contains physical properties of the materials used in the shoe industry. This database can be tailored with materials used exclusively by a specific shoe manufacturer [Figure 6(a)].

The user selects the required tests in the third step of the VSTB Wizard [Figure 6(b)]. In the fourth step, the user specifies all data necessary for performing the required tests. Bending, torsion, stability, shock absorption, metatarsus and heel pressures require data with respect to the Sole materials [Figure 7(a)], while Thermal Comfort uses information which is divided in shoe zones and layers per zone [Figure 7(b)]. Finally, weight utilises the material information for all shoe parts.

All user-defined parameters are checked in the fifth step of the VSTB Wizard, while all tests are performed in the sixth one. The seventh step of the VSTB Wizard, invokes the Performance Evaluator module to present the test results to the user. For most of the tests the result is a single score as it is shown in Figure 8(a). For the thermal comfort test a graph is presented giving the score-performance of the shoe with respect to the environment temperature [Figure 8(b)], while the Fitting test result is shown with respect to the target population and the corresponding fitting percentages [Figure 8(c)].

6 Industrial trials – validation

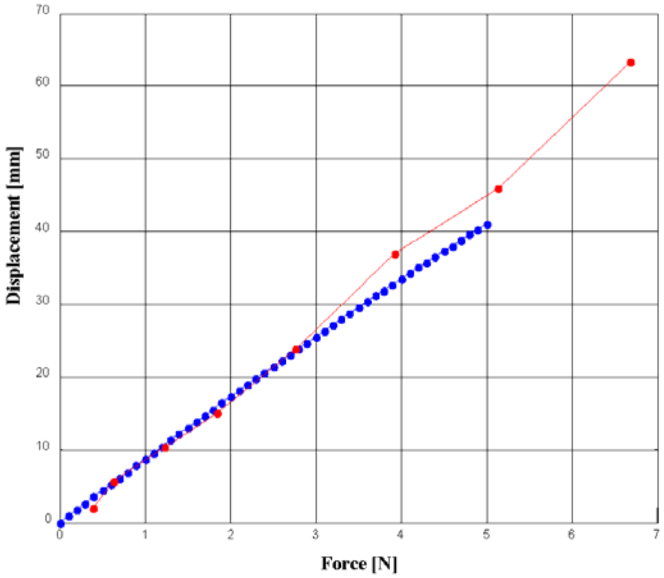
The tests implemented in VSTB have been validated with the aid of footwear companies involved in this research. Individual tests have been assessed by comparing the simulation results with the results of real tests carried out in lab environment. The validation outcome is quite promising since the simulation and lab results match closely. Validation results concerning the thermal comfort test and cushioning tests can be found in Azariadis et al. (2007).

For the bending test, a load is applied to a real and virtual shoe measuring the bending stiffness and the resulting values are demonstrating a good correlation as it is shown in Figure 9.

Experiments with the torsion test verify the existence of a good correlation between the simulation results and the physical tests as it is shown in Figure 10. Again the corresponding angle distortion and torsion have also been calculated using the torsion stiffness.

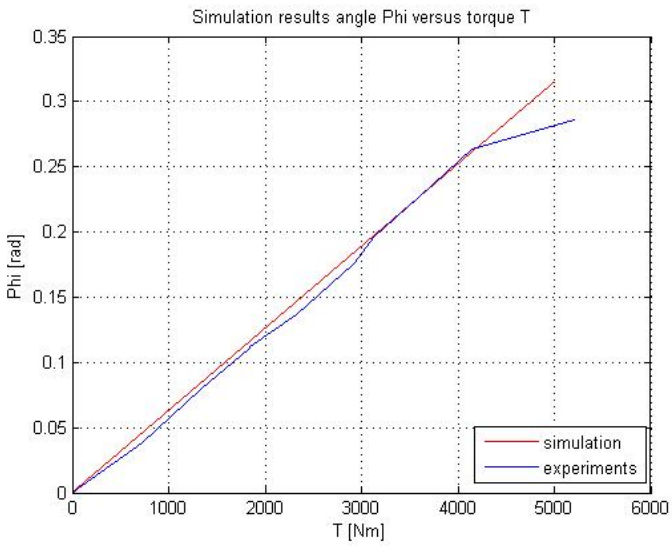
For the validation of the stability test, two different commercial materials 'Loopzool' and 'TPU' have been utilised. Blocks of these materials have been used in a stability set-up to measure the relevant parameters. In particular, a block of materials is pressed downwards while the plate where the block is placed moves horizontally. The point where the system collapses is considered as the point of instability. For each material three experiments are performed (see also Table 1, three rows per material). All relevant parameters are calculated from lab measurements which are then compared with the simulation results. All results concerning the angle of instability *alpha*, the deformation, and the metacentric height are listed in Table 1.

Figure 9 Validation results for bending (see online version for colours)



Notes: In red the experimental bending results, and in blue the simulated results.

Figure 10 Validation results for torsion (see online version for colours)



Note: In red the experimental torsion results, and in blue the simulated results.

Table 1 Stability: experimental vs. simulation results

Material	*Alpha (deg)*	*Deformation (mm)*	*Metacentric height (mm)*
Lab experiment			
Loopzool	4.55	6.75	–2.87
Loopzool	3.13	5.91	–2.71
Loopzool	4.63	5.72	–2.33
TPU	4.26	6.64	–2.86
TPU	3.55	6.13	–2.75
TPU	3.56	5.81	–2.59
Mean Loopzool	*4.10*	*6.12*	*–2.64*
Mean TPU	*3.79*	*6.19*	*–2.73*
Simulation			
Loopzool	4.31	6.25	–2.67
TPU	4.19	6.51	–2.81

In addition to the above, a real commercial sole named 'TRAXX' has been used to evaluate the stability simulation. The results are included in Table 2.

Table 2 Stability: experimental vs. simulation results using the commercial sole 'TRAXX'

Angle (deg)	*Deformation (mm)*	*Metacentric height (mm)*	*Sole name*
Lab experiment			
5,19	16.091	–7.287	TRAXXm1
5,78	17.295	–7.709	TRAXXm2
Simulation			
6,08	18.046	–7.905	TRAXXm1
5,99	18.153	–7.995	TRAXXm2

As it can be seen the difference between the real and the estimated stability metacentric height is less than 3.5% in all experiments.

7 Conclusions

In this paper, a virtual-engineering framework called as VSTB is presented. The purpose of this system is to support footwear designers in order to efficiently develop new shoe concepts that meet specific functional criteria. The proposed system includes the following main features:

- Involves ten functional criteria for determining the performance and the usability of a shoe according to its intended use. Traditionally, these criteria are normally measured in biomechanical labs.
- The overall system architecture is independent of any specific CAD system (commercial, freeware or research) since the simulation processor can be accessed through a set of specific xml-coded input/output files.

- All test results are presented to the designer using a visually friendly method in order to ease the understanding of the various scores.

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. Future research is aimed at two directions:

a improving the underneath DF models by adopting even more realistic shoe simulations

b integrating the VSTB within web-based collaborative environments for supporting all aspects of shoe design and manufacture.

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