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ENGINEERING DESIGN OPTIMIZATION OF HEEL TESTING EQUIPMENT IN THE EXPERIMENTAL VALIDATION OF SAFE WALKING

Abstract: *Experimental test methods for the evaluation of the resistance of heels of ladies' shoes in the case of impact loads are fully defined by International Organization for Standardization (ISO) procedures that indicate all the conditions of experiment. A first Standard (ISO 19553) specifies the test method for determining the strength of the heels in the case of single impact. The result offers a valuation of the liability to fail under the sporadic heavy blows. A second Standard (ISO 19556) details a method for testing the capability of heels of women' shoes to survive to the repetition of small impacts provoked by normal walking. These Standards strictly define the features for two different testing devices (with specific materials, geometries, weights, etc.) and all the experimental procedures to be followed during tests. On the contrary, this paper describes the technical solutions adopted to design one single experimental device able to perform impact testing of heels in both conditions. Joining the accuracy of mechanic movements with the speed of an electronic control system, a new and flexible equipment for the complete characterization of heels respect to (single or fatigue) impacts was developed. Moreover a new level of performances in experimental validation of heel resistance was introduced by the versatility of the user-defined software control programs, able to encode every complex time-depending cycle of impact loads. Dynamic simulations permitted to investigate the impacts on heel in different conditions of testing, optimizing the machine design. The complexity of real stresses on shoes during an ordinary walk and in other common situations (as going up and downstairs) was considered for a proper dimensioning.*

Keywords: *Ladies' shoe, Heels, Impact test, Fatigue, ISO 19553; ISO 19556*

1. Introduction

High-heeled shoes for women are shoes which increase the heel of the wearer's foot much higher than the toes, 9 cm or higher. They are often seen as having more sex appeal, giving the impression of longer and slender legs, and are thus normally dressed by women for special occasions or social outings. Shoes with high heels have been creating a significant debate in the medical sector, with many doctors announcing that

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severe damages in feet have been caused almost entirely by this wear (Chang-Min et al., 2001). And higher heels are progressively riskier and more problematic in the gait; tripping is much more probable, and the risk of injury to the feet, toes or ankles is similarly increased (Mandato, 1999). Shoes with high heels incline the foot forward and down while bending the toes up; thus the food is forced into unnatural position, causing them physical problems (Yung-Hui and Wei-Hsien, 2005). But even without considering the negative effects connected to long-term utilization of high-heeled shoes (Frey and Ne, 2002), progressively higher and thinner heels are progressively riskier for unexpected cracks of the heel and crash of the women (Fig 1).

Also shoes producers start to be worried about these accidents. In fact, they are always more often obliged to pay for damages due to the non perfect manufacture that lowers the usual safety of the other shoes. For instance, a top-class brand refunded 17.000 Euros for a sprained ankle by decision of an Italian Court on October 27th 2005. Moral damages related to wedding shoes broken heels cost a 1500 Euros fee to another shoe producer even without any physical damage to the bride.

A safe heel becomes a fundamental aspect of shoe design. In the last years, designers try to combine style and product reliability introducing in a mature market innovations in materials and processes.

Figure 1. Common failure for heels and an example of potential consequences

In general terms, shoes' designers and manufactures are mainly interesting to

- find methods for improving the heel and sole design from a mechanical point of view
- increase wear and fatigue resistance by new design solutions, materials and technical expedients
- improve the connections between different parts of the shoe
- evaluate reliability and safety by accuracy and standard procedures

In other terms, shoes' designers and manufactures are progressively moving their attention from style to technology, transforming the design of a high fashion shoe in a high-tech product.

Following the trend, this work aims to design a new heel testing machine, able to:

- evaluate the heel resistance to (single) impact
- evaluate the effect of wear and fatigue on heel in the case of multiple impacts
- provide an equipment fully in line with standards
- offer additional functionality and the largest industrial applicability.

In particular, the research was realized by the following steps:

- analysis of the standards for testing heels;
- benchmarking of commercial testing devices;

- patent analysis and anteriority search;
- analysis of the scientific literature on biomechanical aspect of walking;
- measurement of the forces and deformation during an ordinary walk
- simplified numerical simulation of walking
- model development on the interactions between testing device and heel
- design and optimization of testing equipment

2. State of art

2.1 Analysis of standards

Nowadays a large number of ASTM and ISO EU standards deals with women shoes and safe footwear.

One fundamental aspect for safe walking is the hell attachment and its resistance. This requirement is so crucial that the traditional ASTM F694 standard, lunched in 2002 and refreshed till 2008 developing a standard method for testing heel-attaching resistance in the case of women's shoes was superseded and redefined in the ASTM F2232. The past F694 developed a test method covering the determination of resistance in heel attachment in women's shoes applying a static force to the heel. In this wide standard, valid for heels higher than 38 mm, it was considered that shoe heels may be realized by a large gamma of materials, including rubber, plastic, leather, or even wood. Adding heels and shoe bodies may be connected using screws, staples, nails, glue, cement, or a combination of these. The recent evolution, the F2232, approaches the problem of safe walking in a more general way recognizing that the heel represents a fundamental element of the shoe and that the strength of their connection is a significant parameter in guaranteeing the safety in walking, as well as the longevity and serviceability of the shoe.

In practice, this test method, as for the previous one, covers the determination of the force required to detach the heel from footwear through the application of longitudinal tensile force at a constant displacement rate. Longitudinal forces are considered the most appropriate to simulate the most common heel failure modes. The minimum heel height to perform valid test is reduced to 20mm (from 38mm) enlarging the range of applicability on women's medium and high heeled footwear. This test is designed to be rapidly performed on each new style shoe and when any changes are made in the design, material or method of shank or heel area of the shoe, or both, or in the attachment of the heel in an existing shoe.

The desire to transform the ASTM F2232 in a practical and quick standard for improving of safe walking is also demonstrated by its explicit connection to additional norms, generally used for managing experimental tests. For instance, direct connections were established with the ASTM E29 describing how to use significant digits in test data to complain with specifications or with the E105 and E122 dealing with probability, samples size of lots and precision.

Moving in Europe, a substantial correspondence exists between ASTM and British & European Standards (BS EU and EN ISO) that also concede great attention to the hazardous effects of a wrong shoe design or imperfect manufacturing. In particular, ISO prefers to keep an approach toward the shoe considered as a whole, even if each test method stays focused on a specific part. Thus, while the BS ISO 12785 examines the heel attachment and the EU ISO 177708 regards the upper sole adhesion, the EN ISO 19958 is concentrated on the top piece retention and so on.

Beyond the general interest in defining accurate test methods, during the past years additional effort has been dedicated to the design, development and validation of testing machines, including special sections where procedure for their appropriate use have been established. In ASTM, for instance, it is explicitly recognized that equipment can be affected by criticalities in terms of calibration in the way that specific standards have been defined for assuring a constant repeatability of measures. It is the case, e.g., of the ASTM D2047 test method that establishes a compliance criterion relating static coefficient of friction measurements of flooring surfaces with human locomotion safety. The compliance criterion is based on extensive experiential data from residential, commercial, industrial and institutional walkway surfaces. At the same time, the ASTM D6205 details how to calibrate the equipment used for these tests (the James Machine). In fact, it was demonstrated that, over significant time and repetition in use, this equipment (as many others) tends to misalignments in their cinematics, giving evidence of anomalous readings. The frequent validation of results generated by this procedure by comparison with the previous ones, can provide a convenient indication of the exact moment when the equipment cannot be longer considered inside its interval of calibration and, then, its further use is not suggested since precise and reliable measures can no longer be waited.

2.2 Selection of standards

This paper deals with two specific EU ISO standards describing the test methods used for the evaluation of resistance of heels in the case of lateral single impacts and fatigue impact loads. It intends to propose a new equipment able to perform both tests in a simply and functional way. In particular, the design of the new test machine was specifically realized according to ISO 19953 and ISO 19956 procedures that strictly define the main characteristics (geometries, materials, etc.) for the equipment.

ISO 19953 describes the lateral impact tester as an apparatus that includes:

- Pendulum, consisting in a circular steel bob of diameter (108 ± 1)mm and thickness (49 ± 2) mm, fixed by a circular steel shaft of diameter (25 ± 0,5) mm to a hub, on the bearing axle of diameter (75 ± 1) mm. The distance from the centre of the bob to the centre of the hub is (432 ± 2) mm. The moment of the pendulum when it is held horizontally is (17,3 ± 0,2) N·m.
- Striker head, consisting of a strip of metal (6,0 ± 0,5) mm thick, (25,0 ± 0,5) mm wide and (35 ± 2) mm long with the striking edge rounded to a radius of (3,0 ± 0,5) mm. The head is fixed rigidly to the pendulum bob so that the striker tip and centre of the bob lie on the same circle of swing of the pendulum and are (89 ± 2) mm apart. Energy scale for the pendulum, calibrated in increment of 0,68 J, from 0 J to 18,3 J. A marker attached to the pendulum moves over this scale and enables the pendulum to be set up to the desired potential energy.
- Base clamp, for holding the metal mounting tray and for adjusting it vertically and horizontally to achieve correct alignment of the heel tip. the apparatus is not firmly mounted there is partial loss of energy on impact, thereby producing false results.

ISO 19956 describes the heel fatigue-testing apparatus as a motor-driven pendulum which can deliver blows to a test specimen assembly, each blow having an energy of 0,68 J, at the rate of one blow per second, including:

- Pendulum, consisting of a circular steel bob of diameter 57 mm ± 1 mm and thickness 20 mm ± 1 mm, which is fixed by a circular shaft of diameter 12,5 mm ± 1,0 mm to a hub on the bearing axle. The distance from the centre of the bob to the centre of the hub is 152 mm ± 2 mm. The moment of the pendulum when is held horizontally is 0,68 N·m ± 0,02 N·m.

- Striker head, consisting of a strip of metal 6,0 mm ± 0,5 mm thick, 20 mm ± 1 mm wide and 35 mm ± 2 mm long with the striking edge rounded to a radius of 3,0 mm ± 0,5 mm. The head is fixed rigidly to the pendulum bob so that the striker tip and centre of the bob lie on the same circle of swing of the pendulum and are 63,5 mm ± 2 mm apart.
- Rebound damper, for the pendulum.
- Base clamp, for holding the metal mounting tray and for adjusting it vertically and horizontally to achieve correct alignment of the heel tip.
- Counter, for recording the number of blows.
- Overshoot cut-out device, which operates when the pendulum overshoots a broken heel stem at complete failure.

Both the devices (shown in Figure 2 and 3) have to be clamped on to a solid built-in bench or on to a rigid free-standing frame anchored to the floor.

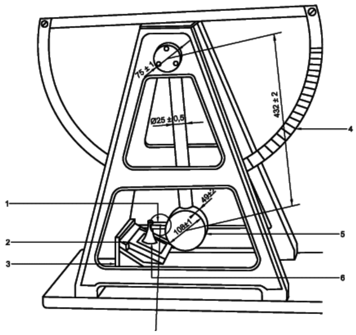

Figure 2. Lateral impact tester (ISO 19953)

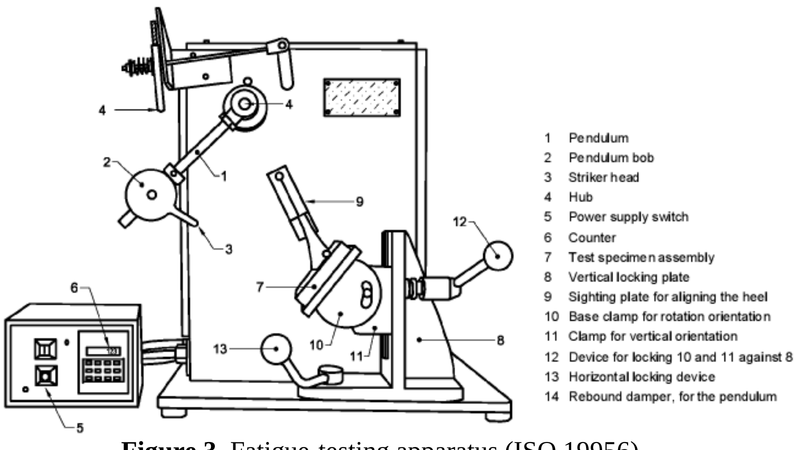

Figure 3. Fatigue-testing apparatus (ISO 19956)

If these apparatuses are not firmly mounted and fixed, there is a partial loss of energy on impact, thereby producing false results.

2.3 Analysis of anteriority

The importance of developing an efficient machine for heel testing can be recognized noting how many similar investigations exist and the technical efforts dedicated to this topic. In (Monckton et al., 2002), for instance, the design and full deployment of an automated testing system for footwear was presented. Inside this study the shareable scope of providing a cheap and consistent method for evaluating the performance of shoes was obtained by an automated testing system for footwear, but in the limited case of athletic shoes. Particularly noteworthy is the part related to the emulation of the interaction between foot and ground during different movements (as walking, running, stopping, side shuffling and jumping). Furthermore, the machine was designed to consider a large gamma of different parameters as weight, shoe size, gender, and running style. From these concepts, some inspirations for the present research emerged.

In (Norton, 2006) an innovative shoe testing apparatus was not only designed, but also patented and its operation method fully detailed. This procedure of test intends to replicate the stresses on shoe in the phases of walking or running and during, in particular, the midstance subphase when the total weight of the woman's body is being shifted across the planar surface of her foot. Foot pain is often related to shoe with less flexibility causing incorrect strides or faulty pronation in the midstance subphase of walking. Furthermore, this apparatus can be utilized to evaluate various brands of shoes, but also to determine when an old shoe needs to be replaced.

In (Oman et al., 2004) the use of particular midsoles and a procedure for designing midsoles were proposed. The midsole was considered as a plurality of cells able to extend generally upward from a generally flat support structure. Then, it is offered the capability to temper, in a selective way, the reaction forces of ground resulted by activities associated with the application for which the shoe midsole is designed. The midsole includes a multiplicity of areas. The properties of shock attenuation of each area can be related to the specific cells' geometry in that area and particular material composition of the midsole. From a correct distribution of pressure on the whole shoes, not only a comfortable utilization but also a safer walking can be obtained, considering the reduction of peak of load on heels and other critical shoe parts. This investigation provided useful information on dynamic walking principles toward their simplification.

In (Singleton et al., 2006) the whole shoe, instead of its singles parts, is at the center of the attention: a high-heeled fashion shoe is patented, characterized by special features in terms of comfort and performance. This special footwear uses a heel equipped by a resilient compressible element. The system allows the heel to be lowered at heel strike to approximate a normal walking pattern in low-heeled shoes. The footwear also includes a midfoot structure as support that, acting as a sprung footbed, or a sling and reinforcement girder, permits to reallocate loads from the forefoot to the midfoot.

Regarding the most relevant issues to be considered in the design shoes, an interesting synthesis is proposed by (Reinschmidt and Nigg, 2000). Even if primarily focused on sportive shoes, its conclusions can be easily extended to heeled shoes and court shoes when identifies, between the most important functional factors, three design parameters: injury prevention, comfort and performance. In particular, aspects as stability respect to the lateral movements, flexibility in torsion, control during traction and, finally, cushioning can assume an important role inside a new design strategy, to reduce the risk of injury in the case of court shoes.

Despite of a huge number of investigation, research in the area of shoe safety and perfect design is still sparse without a definitive response. Experimental tests, even when limited to the application of standard procedures like in the present case, can reinforce the general knowledge toward safer shoes.

3. Engineering design of the new equipment

3.1 The general design

The project aimed to design a single testing apparatus suitable, at the same time, for two different experimental procedures: impact and fatigue. This functional concept represented the starting point in the design process. Nevertheless, considering the remarkable differences between specifications ruled inside the two ISO standards, this functional integration was possible only developing stratagems for modifying impact geometry and energy.

In particular, the equipment is powered by a mechanic system able to lift up the pendulum in accordance to each specific procedure. By a PLC, in fact, it is possible to control the position and fall of the pendulum, in terms of height as fundamental parameter for the validation of lateral impact tests. At the same time, since the net difference in impact energies at stake, two pendula were designed: a heavy one for single impact tests and a lighter for fatigue. Weights were strictly defined referring to the standards.

Adding, in the case of fatigue test, the PLC also permits to adjust the impact frequency to be in line with the ISO 19956 requirements, but for performing fast and accurate tests, too. Proper sensors and instruments are installed and used for counting and measuring.

Thus, the complex goal to create a practical way to modify the geometry of the apparatus, giving the correct equipment configuration respect to two different testing procedures, was obtained.

In particular, the technical solution passed by:

- flexible mechanical movements, valid either for the case of an accurate and single hit or quick and repeated movements;
- two pendula with different mass and shape and, consequently, impact energy;
- a uncoupling system that permits to change the pendulum by an easy and fast operation;
- a regulation platform for heel positioning that permits every arrangement necessary for the tests.

In Figure 4 and 5 the main features of the testing device are presented.

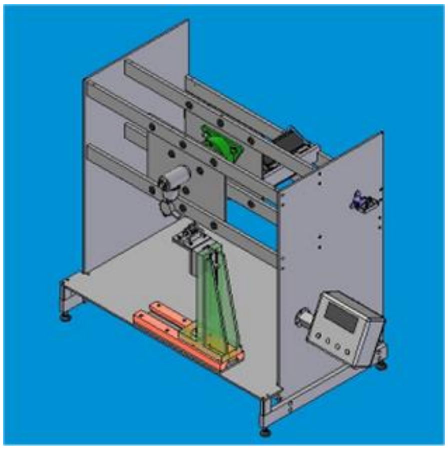

Figure 4. Testing device general view

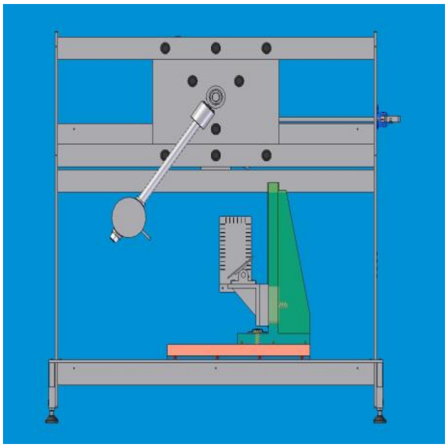

Figure 5: Frontal view with pendula and alignment system

3.2 The pendula

The flexibility in mass of pendula is given, as anticipated, by differences in the geometrical dimensions (section and length) of the two handles (made by Aluminium Ergal 55 with density of 2.71 g/cm^3). The connection between the handle and the shaft (made of C40 Steel with the density of 7.85 g/cm3) is guaranteed by a new solution of fastener, realized by a metal ring, that permits manually locking and unlocking operations without using jigs. A security half-ring avoids unscrewing of connection related to continuous impact during the fatigue tests. The pendulum is strictly fixed to the handle by tab (UNI 6604-B 3x3x20 and UNI 6604-B 3x3x20), hexagonal nut (ISO 8673-M18-8 and ISO 8673-M8-8) and rosettes (UNI 6593 20x34 and UNI 6593 11x21). Materials for pendula and handles are defined taking in count of the inertial moments in the horizontal position (for standards: 17.3+\-0.2 Nm for lateral impact, 0.68+\-0.02 Nm for fatigue impact), with an angle of 90° respect to the relaxed position.

3.3 The platform

The flexibility of the apparatus and, subsequently, the capability to realize the two different experimental procedures, is also assured by the particular solutions used for the supporting platform on which the heel is fixed. This moving platform is realized to give to the heel all the degree of freedom for the correct positioning during the two different experimental configurations. At the same time, the rigid structure permits to absorb the impact loads during the tests. The platform has two orthogonal guides for horizontal (X) and vertical (Z) movements; a pivot by which platform is fixed, permits movement along and around the other axis (Y). The correct position for the heel (its geometry changes for different models of shoes) and for the impact point is determined using the proper pendulum and, for reference, two mobile tabs, installed at different height since the different length of the each rod.

3.4 The moving system

The flexibility in the mechanical movement of the pendulum is a fundamental step to join different functions in the same equipment. The system is realized by one brushless engine and a shaft on which the pendulum is rigidly connected (Figure 6). The solution of brushless engine permits an accurate control of the rotation angle (and energy) of the pendulum during the lateral impact tests, directly defining the rotation of engine by PLC. During the fatigue tests, the brushless engine permits to control the angular speed. But, at the same time, the PLC can freely modulate angular speeds and rotation angles even creating new sequences of impact conditions and realizing different profile of test. The possibility to create complex load profiles enlarges the research field to more sophisticated experimental tests, even to the direct reconstruction of the heel stress conditions during real applications.

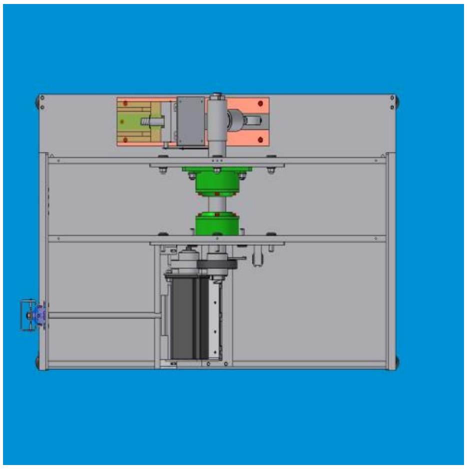

Figure 6. Power transmission system

Motion is transmitted by a specifically designed clutch solution (Figure 7) realized by a cam pulley (made of steel 16CRNI4 UNI 7846), connected to the engine and to another pulley (made of steel St

33NICRMO3 UNI 7845 with a Nichel-T surface treatment) connected to the shaft with a lateral surface covered by *vulkolan* (with 90±4 shore). The first pulley has a particular profile able to interfere with *vulkolan* on the cam pulley only for fixed sector of 90° and, consequently, to lift the pendulum to the maximum rotation angle of 90° against a block system. During fatigue test, engine turns in the same direction and pendulum lift up to 90° every 360° of shaft rotation. By means of the PLC, the angular speed can be changed and the proper frequency of impact heel-pendulum arranged. To avoid a complete 360° rotation of pendulum, related to the inertial forces, a shock absorber system blocks the pendulum at 90°, unlock the lever leaving the pendulum able to fall down in a free-fall condition according to the standards. For single impact lateral test, the lift-up angle for pendulum is defined by PLC according to the ISO standards. Then, a specifically designed knockoff system unlocks the shaft for the engines so that the pendulum is free to fall down. Manually moving a specific lever, the knockoff system unlocks a pivot, pre-tensioned by a spring that quickly push the first pulley (on the engine) away from the second pulley (on the shaft). In Figure 8 the pendulum releasing system is shown while Figure 9 details the pivoting motor and anti-rebound systems.

Figure 7. Clutch solution

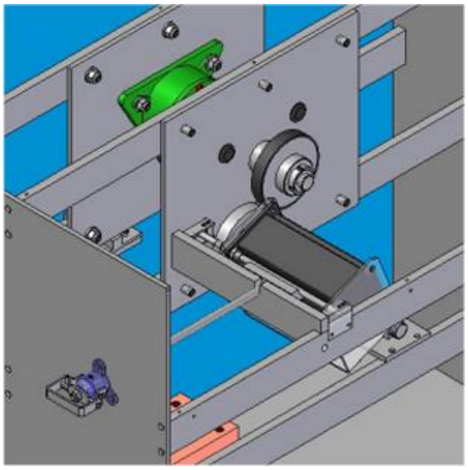

Figure 8. Pendulum releasing system

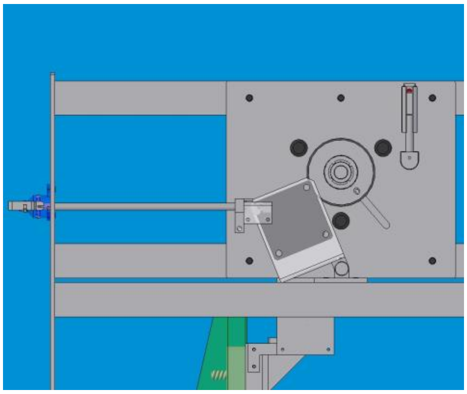

Figure 9. Pivoting motor and anti-rebound system

The engine box is mounted on the framework by another pivot. In this movement, the engine rotates around its pivot with an equivalent linear displacement of 2.5 mm, enough to stop the connection between engine and shaft.

3.5 The rigid framework

The framework is realized by 2 lateral sheets, 540x1000mm of dimensions and 8mm of thickness, connected by 9 girders of 15x60mm and 1000mm of length, realizing a rigid structures able to guarantee high stability during tests. Two supports for commercial bearings (code SKF7225) are fixed on two metal sheets with 8mmthinkness, connected by bolts on the rigid girders. Framework is completed by 2 further girders, with little plastic legs, adjustable on vertical axis, to obtain the best regulation during the experiments.

3.6 The instruments

The device is equipped by several instruments for control and measurement.

The PLC and software control the brushless engine modulating angular speeds and rotation angles. A special load cell replaces the pivot on which is mounted the supporting platform for the heel positioning. This load cell gives an electrical signal proportional to the applied load. The output signal is visible on PLC display. Adding acoustic measures, it would be maybe possible to also evaluate the material damage as proposed in (Mahdian et al., 2017) for composites. The platform has a specific ruler that permits to evaluate geometric dimensions relatively to the heel or between heels and strain gages.

3.7 The double configuration

In brief, thanks to the elasticity of this acquisition system, coupled with the flexibility offered by the double mechanical configuration, the same equipment can provide experimental tests both for single impact tests (Fig. 10, left) or fatigue tests (Fig. 10, right), simply acting on pendulum’s dimension, fixture and alignment system. This result is a step forward respect to the traditional heel testing machines. By this equipment it is possible to perform an experimental validation on heel’s resistance in accordance with both standards, the ISO 19953 and 19956 with evident advantages.

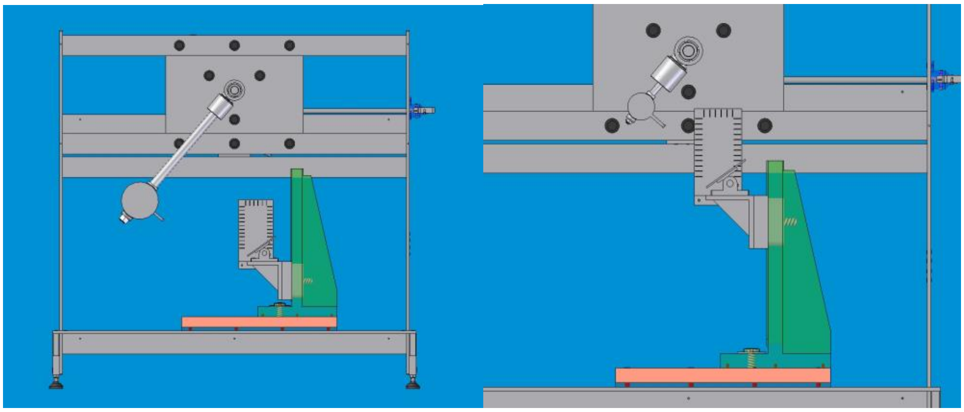

Figure 10. Equipment with double configuration, used for single impact (up) or fatigue tests (down) by acting on pendulum’s dimension, fixture and alignment system

4. From design to calibration

The general flexibility in tests, offered by the possibility of quick changes in loads configuration and intensity, speeds, frequency, etc., together with the adoption of an advanced network of external and integrated sensors for stress/strain monitoring, also transform this testing machine in an useful equipment for all-purpose investigations. In fact, far beyond from representing a way for a simple validation of standards by the application of normalized tests and loads, it can be employed for exploring the resistance of heels respect to a large range of dynamic and fatigue conditions. With this scope, it assumes a different meaning the following steps regarding the equipment’s calibration by experiments and simulations.

Whatever equipment is involved, an

appropriate and desirable target would be the development of an overall calibration curve able to relate the parameters used during the experiment to the stress profiles generated in the heel under testing and, at the same time, the recognition of the equivalence between these stresses, induced by experiment, and the most common conditions of use for shoes.

This target was approached combining measures of deformation on heels during walking and in other common situations, with two different Finite Element (FE) simulations. In the first one, a simplified FE modelling of hell's conditions during walking was realized. The simplification is related to the fact of considering the walk as a sequel of quasi-static conditions with the whole static load (the woman's weight) applied in different parts of shoes and with forces differently orientated. Contrarily to what might be expected bearing in mind the complexity of human walk, this simplification was considered not so far from reality in the specific situation of high heels walking. In the case of high heels shoes, not even remotely anatomic, the typical woman walk is represented by a relatively slow and hampered sequel of sudden changes of weight between toe and heel (Hong et al., 1999). The second FEM simulation was focused on investigating the impact of pendula on heel in the way to relate the stress-strain condition in the heel with the main experimental parameters.

5. Preliminary experimental measurements

5.1 Materials

According to manufacturers' information, soles and heels shoes are commonly realized by 2 different thermoplastic materials: ABS and PMMA. A comparing overview of mechanical properties for both materials is reported in Table 1. These properties were used both for performing simulations or evaluating the experimental measures.

Acrylonitrile butadiene styrene, better known as ABS, is a thermoplastic material, commonly used to produce light, but stiff products by moulding processes. It is obtained by polymerizing styrene and acrylonitrile in the presence of polybutadiene. According to the proportions of these elements, different properties can be offered to the ABS. The nitrile groups makes ABS stronger than pure polystyrene. The styrene gives the plastic a shiny, impervious surface. The butadiene, a rubbery substance, provides resilience even at low temperatures. Thanks to that, ABS is able to combine the strength and rigidity of the acrylonitrile and styrene polymers with the toughness of the polybutadiene rubber. Furthermore, the resistance during impact could be conveniently improved by change in the chemical solution and, in particular, increasing the polybutadiene. Material stability under loads is also excellent and almost stable between −25 and 60 °C.

Polymethyl methacrylate, often shortened as PMMA, is a thermoplastic and transparent plastic, commercialized in different tradenames (the most famous is Plexiglas). Also largely known as acrylic glass or simply acrylic, this resistant plastic is often utilized as an alternative to glass. Respect to glass, in fact, PMMA is two times lighter (with a density between 1150-1190 kg/m^3), with a higher impact strength, softer and more workable. Adding, PMMA does not shatter as any other fragile material, but instead breaks into large dull pieces.

However, in using these (or other) material properties as a way for driving the shoes design, it is noteworthy that, in the case of plastics, these values can largely vary in consideration of the specific mix of their constituents, different processes parameters or, even, manufacturers. Adding, these properties can be easily effected by unexpected phenomena of degradation and aging. The situation has been fully invested in the case of polytetrafluoroethylene (PTFE), better known with the commercial name of Teflon, by Bignozzi et al., 2015, Giorgini et al., 2016, Fragassa et al., 2016. In general, it is possible to say that a direct characterization of chosen materials would be preferable, instead of accepting nominal values from technical sheets.

Further uncommon solutions for materials (e.g. reinforcements realized by natural fibers (Fragassa, 2016a) or nanofibers (Fotouhi et al., 2016) or in treatments (Zivkovic et al., 2016) are also under surveillance by shoes' producers since the evidence of their convenience on similar market segments, but they are far away from representing an applicable material solution in footwear.

Table 1. Comparison of mechanical properties between ABS and PMMA

Property *(at 23 °C)*		**ABS**	**PMMA**
Tensile Strength	*MPa*	45.8	68.9
Flexural Strength	*MPa*	75.8	117.2
Compressive Strength	*MPa*	46.5	70-120
Elongation at Break	*%*	20	2-5
Tensile Modulus of Elasticity	*MPa*	2200	3000
Flexural Modulus of Elasticity	*MPa*	2275	2758
Hardness	*Various*	R105	M-93
Density	*gr/cm^3*	1.024	1.218
Tensile Strength	*MPa*	45.8	68.9
Flexural Strength	*MPa*	75.8	117.2
Compressive Strength	*MPa*	46.5	70-120
Elongation at Break	*%*	20	2-5

5.2 Real Load Measurements

The complex shape of the stress curves in different key-points of the 11-cm-high heel during an ordinary walk and in particular situations (as going up and downstairs, jumping, sitting in a car, etc.) was evaluated in (Minak et al., 2017) in experimental measurements. In brief, the heel was substituted by a strain gage instrumented aluminium hollow cylinder with the capability of measuring the axial force by a quarter of bridge connected strain gage, the bending moment in two sections and two directions by eight half bridge connected strain gages and the torque by means of four full bridge connected strain gages. This load cell was calibrated by known loads and a quite diagonal calibration matrix was found. The subject for this study was a 60 kilos young and healthy woman without any foot or postural problems. Data were acquired by Leane multichannel portable system shown in Figure 11.

Figure 11. Testing phase

In Figure 12 typical stress trends in different conditions of shoes' use are shown. Material properties permitted to convert the observed strain response in stress solicitations. Also the sole was instrumented to compare the experimental results with FEM stress analysis evaluation creating a valid model for interpretation and prediction of the experiments.

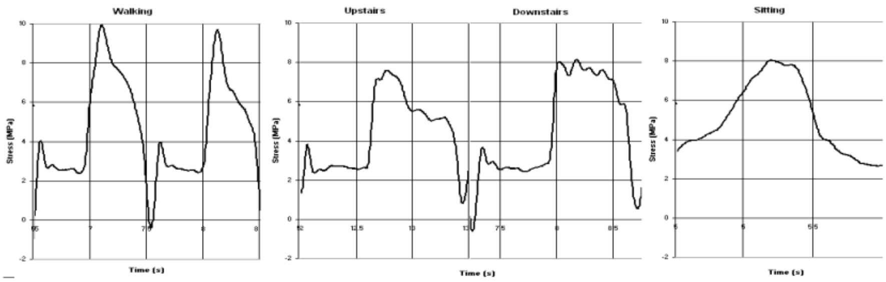

Figure 12. Stress curves in different experimental conditions

In particular, the low measures of stress confirmed the simplification in walk modelling.

6. Toward FEM simulation of experiments

6.1 A simplified FEM simulation of walking

Building an accurate model for the simulation (Figure 13) of walking is a very complex problem that involves different aspects of bioengineering and motion sciences: weight, stature, posture, speed are just only few personal parameters that can completely change the distribution of pressure on soil and heel. But other aspects, connected with the shoe, may strongly influence the way to walk and the accuracy of every theoretical model: soil shape, heel height, global comfort of the shoe, etc.

Nevertheless a proper description of the interaction between human body and shoe during the different conditions of usage is only slightly relevant for the engineering design optimization of heel testing equipment since, by preliminary tests on heel only the bending moments were found to be really important for the heel resistance.

Consequently, a simplified model of external loads were developed dividing the single step of the walk in three sequential phases:

- backside muster
- central transfer
- frontal delivering.

Considering the influence of the second foot that bears a portion of global load, it was chosen a normalizing factor for the body weight (60 kg in the simulations) of, respectively, 40%, 60%, 100% for the three phases. At the same time the upper surface of the soil is divided in three main areas (heel, central sole, nib) according to state-of-art recommendation on most stressed regions of the moving foot. For each phase, only the corresponding area is progressive loaded. All loads are considered static in each phase and homogeneously distributed on each area.

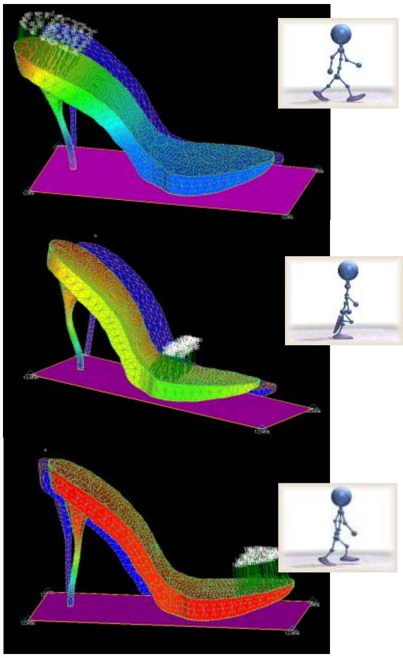

Figure 13. FEM simulation of shoe and heel strain reactions under simplified load conditions

Boundary conditions were initially set in the way that all six DOF was fixed on one single plate with the physical modelling of:

- sole and heel fixed on the floor.

Afterward, for a better FEM modelling of reality, different hypotheses of simplified constrains were taken in count according to the physical modelling of:

- sole or heel horizontally sliding on the floor
- sole or heel vertically rising respect to the floor.

Nastran 10.0 was used for importing and modelling of the shoe geometries and to carry out all static FEM simulations. Mesh of finite elements was created using *Parabolic Tetra 10* element (10 nodes per element) that could approximated all surfaces and sharp edges. Discretization of the model was realized by a mesh of 6022 elements and 10128 nodes.

Properly comparing experimental results and information from FEM simulations, beyond the simplicity of some modelling assumptions, it was possible to develop a qualitative model able to approximately describing the interaction between loads on sole and heel deformations (*direct problem*).

6.2 A FEM simulation of lateral impact tester

Next step was to predict the effect of testing equipment on the whole shoe by simulation of pendulum impacts on heel in different conditions of testing (*reverse problem*).

Using the knowledge of the motion of the system, a dynamic impact analysis was realized. Each simulation considered a pendulum, defined for a specific mass, hitting the heel with a certain speed. Accurate results are possible using a contact theory. In particular, it was necessary to define the contact conditions of elements in shoe and pendulum, with *slave* and *master* elements. Then, it was necessary to define the type of the contact, *friction less* and the method for equation solving, *Pure Penalty*.

A simplified model was also investigated in consideration of low impact speed, able to move the simulation from a complex dynamic analysis to a static FEM evaluation. In this case, the main assumption was that all the kinetic and potential energy of the moving pendulum (easily defined by mass and height of the free fall) is converted, during the impact, in elastic-plastic deformation energy of heel and, in slightest part, of the pendulum. By this concept of equivalence, with a trial-on-error method, a corresponding static force was defined for every motivating configuration of pendulum's mass/height and heel's material. Nastran 10.0 was used for importing and modelling of the heel and pendulum geometries and to carry out all static and dynamic FEM simulations (Figure 14). Mesh of finite elements was created using *Parabolic Tetra 10* element (10 nodes per element).

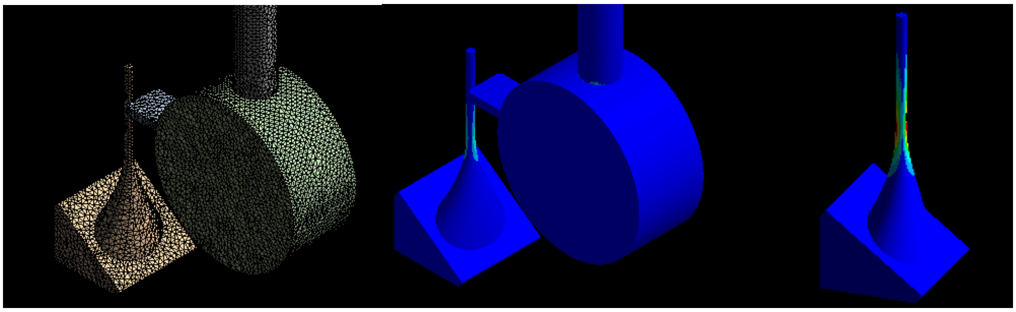

Figure 14. FEM dynamic simulation of impact of pendulum on heel

These and other conditions, used in the numerical simulation were assumed in accordance with the theory of impact modelling proposed in (Pavlovic et al., 2017).

7. Conclusions

An equipment for the complete evaluation of the resistance of heels of ladies' shoes accordingly to ISO standard procedures is proposed. Distinct constructive solutions and several technical expedients permitted to design a single experimental equipment able to perform, by the same device, two different kind of tests on heels:

- a single strong impact provoked by an individual knock (ISO 19953);
- the repeated small impacts provoked by normal walking (ISO 19956).

These methods permit to determine the force required to separate the heel from the shoe applying a longitudinal tensile force. This kind of force is able to represent the most common failure mode for heels, in the way this test represents the first requirement female shoes have to respect. In particular, this test method would be necessary in the case of heels higher than 20mm, condition that represents the most women's medium and high heeled footwear.

The free-fall impact testing device which consisted of an instrumented shaft, accelerometer and position detection transducer was specifically designed to obtain deceleration and deformation in the heel during impact. Peak values of the deceleration and deformation, as well as the time to these peaks from onset of impact, and energy absorption could be evaluated. Delay time for each impact is 1 sec in single impact configuration and 0.5 sec for multiple impact configuration. Thus, this controlled device is also able to perform tailored tests based on the knowledge of the real load on the shoes during normal life. Simplified FEM analysis of the heel under static loads joined with an experimental acquisition of stress curve during normal use of the shoes (ex. walking, climbing stairs, etc.) supported the design phase. An additional FEM analysis investigated the effect of impacts of pendula on heels permitting to relate the experimental conditions to the stress-strain levels in materials.

Next activities will run on two parallel tracks: i) manufacturing and setting up the experimental equipment; ii) improving an accurate FEM dynamic model for a better comprehension of interrelations between the results of impact tests on heels (performed using the new equipment) and the measures on footwear during ordinary condition of use (performed using experimental techniques). This last aspect will permit to extrapolate a final calibration curve for a correct use of equipment, together with a procedure preventing mechanical misalignment and anomalous readings as detailed in (Fragassa 2016c).

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