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NONLINEAR FINITE ELEMENT ANALYSIS AND STRUCTURAL VALIDATION OF SHOCK ABSORBERS USED ON TREADMILLS

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Abstract. *In recent years, the number of people practicing physical activities has grown, with walking and running the most popular choices. However, the continuous practice of these exercises can lead to injuries, especially on the knees. To prevent them, treadmills have efficient shock absorption systems, usually made up of cushions, which reduce the impact forces between the running pad and the person who is walking or running on it. Shock absorbers can generate varying impact absorption conditions, depending on the materials and adopted geometry. If this component is not well projected, maintaining treadmills stability during the run, the person performing the exercise may be injured. Therefore, this study aimed to analyse, through finite element models and experimental tests, the mechanical behaviour, in terms of absorbed energy, of two different models of cushions commercially used on treadmills. The shock absorbers geometries were obtained from each manufacturer and modelled on the SpaceClaim module (ANSYS Inc., USA). Natural Rubber 60 Shore A and TPU (Thermoplastic Polyurethane) materials were used, with both being modelled with hyperelastic behaviour. A static compression experimental test of each shock absorber was performed alongside finite element simulations (Workbench, ANSYS Inc., USA). From the obtained experimental results, the finite element models were validated and the influence of the cushion's geometry on absorbing impact energy was evaluated: both models have a non-linear relationship between applied force and displacement and the rubber damping elastic coefficient is, on average, 19% higher than the constant TPU shock absorber.*

Keywords: *impact, shock absorber, treadmill, finite elements analysis*

1. INTRODUCTION

The knee absorbs the entire impact loading arising from running or walking. Consequently, it is where an injury is more likely to occur (Moreira et al., 2015). When comparing the performance of an exercise practiced wearing shoes or barefoot, the first condition is less efficient to dissipate the ground reaction forces, resulting in an overloading of the lower joints (Moreira et al., 2015).

Controlling the ground reaction forces during physical activities is thus important, as they will determine limb loading and stresses levels on the human body (Kenneth et al., 2017). Decreasing the impact force during the practice of these exercises is essential, as it will prevent injury and improve recovery.

Gyms are usually the preferential choice for several people, as it provides a safe place to the practice of exercises. The main activity in gyms is running or walking on treadmills. According to Kluttenberg et al. (2012), running on treadmills generates vertical ground force reactions equivalent to walking on the rigid ground. Consequently, aiming to reduce the impact loading and improve energy dissipation, treadmills have a damping system, which must take into account a wide range of user's weights, which varies between 40 kg and 180 kg.

One of the main components of a treadmill's damping system is the cushion. It aims, through its body deformation, to absorb shocks, vibrations, and noise. It is usually made of rubber, a highly elastic material, with an elastic modulus up to 100,000 times smaller than steel (Hakanson, 2000). Another material with equivalent characteristics to rubber is the thermoplastic polyurethane (TPU), which has a good elastic memory and high resistance to impact and fatigue, thus being ideal to support the high number of loading cycles that are applied by the user during an exercise (Compostos, 2021).

The Finite Element Method (FEM) is used to analyse the structural behaviour of mechanical components. When a representation of a component made of elastomeric material is necessary for a simulation, it is usually replaced by a linear spring and by a damper. However, this approach does not include the geometrical characteristics of the component, which

are important in the study of a damping system. Consequently, the results usually found in numerical models frequently differ from what is seen experimentally, making necessary the use of appropriate constitutive models (Hakanson, 2000). However, determining a suitable geometry for the treadmill's damping system is a complex task, mainly due to the material and geometrical nonlinearities. Therefore, this study aims to analyse and compare the performance of two different cushions and evaluate their efficiency in absorbing energy.

2. MATERIALS AND METHODS

The damping system of a treadmill consists of three main elements: cushion (1), beams (2) and running surface, (3), Figure 1.

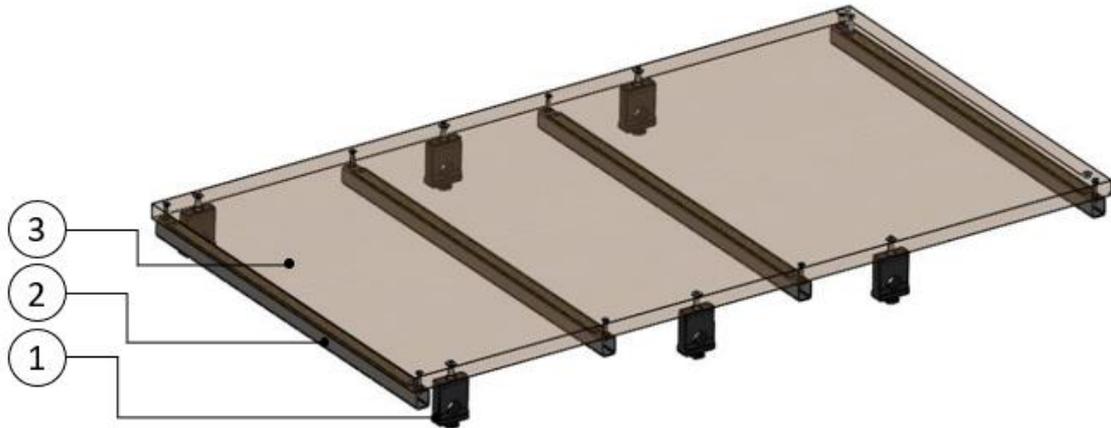


Figure 1. Treadmill damping system (Source – the Author).

Two models of commercially available cushions, from two different manufacturers, were selected. The first model is made of natural rubber (60 Shore A), and the second is made of TPU (90 Shore A). An experimental compression test was conducted to validate the finite element models and to provide a deeper understanding of the mechanical behaviour of the cushions. A compressive and ramping load, from 0N to 1000N, was applied at the top surface of each cushion. Five samples of each cushion type were tested to decrease Mullin's Effect (Godvindhjee and Simo, 1992). From each experiment, a load-displacement curve was acquired. Figure 2.



Figure 2. Compression Test Device (Source – the Author).

Both cushion's geometries were obtained from manufacturers and modelled in the SpaceClaim module (ANSYS, Inc., USA 2019). The first model, Figure 3A, has a rectangular shape, with a hole in the centre, and it is made of Natural Rubber 60 Shore A. The second geometry, Figure 3B, has an elliptical shape, also with a hole in the centre, and is made of TPU.

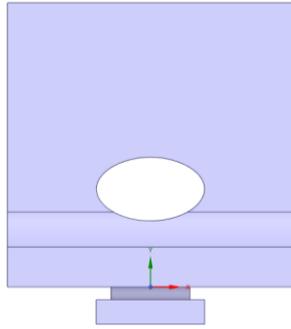


Figure 3A. Natural rubber cushion geometry.

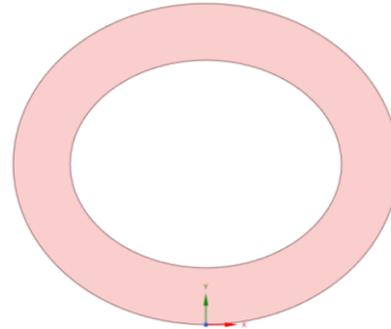


Figure 3B. TPU Cushion Geometry.

For the rectangular cushion made of natural rubber 60 Shore A, a third-order Yeoh material model was used, with material constants provided by Hakansson, (2000): $C_{10} = 0.5829$ MPa, $C_{20} = -0,3804$ MPa, and $C_{30} = 0.9924$ MPa. The Yeoh constitutive equation can be described by the Eq. 1:

$$W = \sum_{i=1}^N C_{i0} \cdot (\bar{I}_1 - 3)^i,$$

where W , C_i , \bar{I}_1 are strain energy density function, the material constants is the strain invariant, respectively.

For the TPU elliptical cushion, an interactive approach was used to find an optimal constant for the first order Neo-Hookean material model, where an initial value was chosen and then optimised according to the experimental results. The Neo-Hookean constitutive equation can be described by the Eq. 2:

$$W = C_1 \cdot (\bar{I}_1 - 3),$$

where W , C_1 , \bar{I}_1 are strain energy density function, the material constants is the strain invariant, respectively.

As both geometries are symmetrical, the analysis was simplified to $1/4$ of the original geometry, and a rigid pad was added on the top surface of the cushions, so that the load could be evenly distributed as it was in the experiment, Figures 4A, 4B, 4C and 4D.

In Figure 4A, the red surfaces are the symmetry surfaces of the finite element model to the original model. In Figure 4B, the yellow surface represents the ground surface of the component on the testing equipment. In Figure 4C, the blue and red areas represent the contact between the inner surfaces of the mass relief section, and the contact between the top plate and the cushion, respectively. In Figure 4D, the red region is the force applied to the model, which is 250N in this case ($1/4$ of the original loading).

In Figure 5A, the red region are the symmetry surfaces of the finite element model to the original model. In Figure 5B, the yellow and blue surfaces represent the ground surface of the component on the testing equipment. In Figure 5C the blue and red region represents and the contact between the top and the bottom plates and the cushion. In Figure 5D, the red region is the force applied to the model, which is 250N in this case ($1/4$ of the original loading).

Mesh convergence was performed with criteria of 1%. For the natural rubber cushion, the number of elements that met this requirement was 33,325. For the TPU cushion, the number was 19,054. The models were solved in Ansys software (Workbench, ANSYS Inc., USA 2019).

3. RESULTS

The maximum displacement for each of the cushions was obtained from the finite element models. For the rectangular natural rubber cushion, the displacement was 13.4 mm at the maximum load of 1,000N. Figure 6A illustrates the displacement distribution obtained in this analysis. It is possible to verify, through the colour scale, the displacement range of each region. Figure 6B depicts the results obtained from both the numerical simulation and laboratory testing. The maximum displacement for the experimental test for this cushion was 13.2 ± 0.5 mm at 1000N.

The TPU elliptical cushion had a maximum numerical displacement of 16.2 mm at 1000N. Figure 7A illustrates the results at maximum load. The constant value that met the convergence criterion for the Neo-Hookean constitutive model was 27.5 MPa. Figure 7B depicts the results obtained from both the numerical simulation and laboratory testing. The maximum experimental displacement was 16.5 ± 0.8 mm at 1000N.



Figure 4A. Schematic of the constraints, symmetry region, of the Natural Rubber cushion.

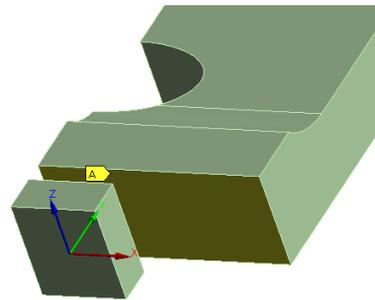


Figure 4B. Schematic of the constraints, support region, of the Natural Rubber cushion.

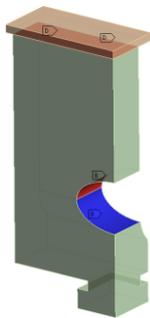


Figure 4C. Schematic of the boundary condition, contact region, of the Natural Rubber cushion.

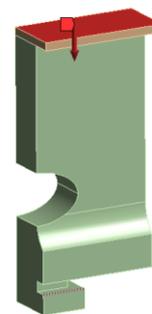


Figure 4D. Schematic of the boundary condition, load, of the Natural Rubber cushion.

Figure 4 – Boundary Conditions for the Natural rubber cushion.

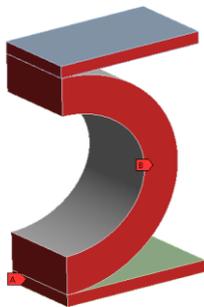


Figure 5A. Schematic of the constraints, symmetry region, of the TPU cushion.

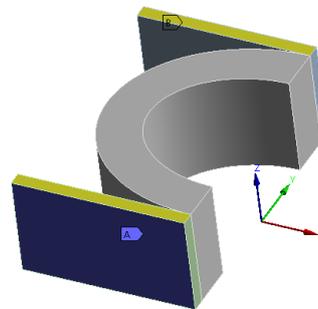


Figure 5B. Schematic of the constraints, support region, of the TPU cushion.

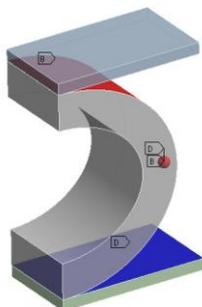


Figure 5C. Schematic of the boundary condition, contact region, of the TPU cushion.

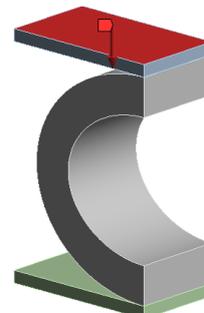


Figure 5D. Schematic of the boundary condition, load, of the TPU cushion.

Figure 5 – Boundary Conditions for the TPU Cushion.

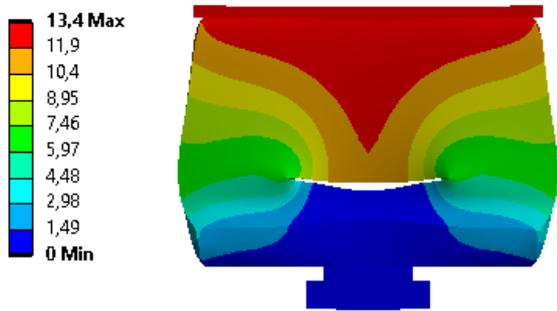


Figure 6A. Displacement of the Natural Rubber Cushion.

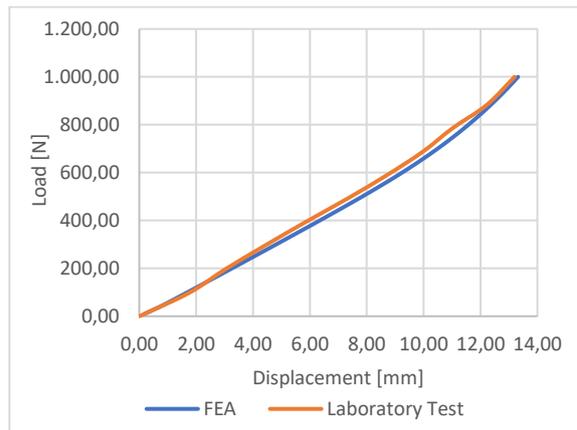


Figure 6B. Force VS Displacement for rubber pad 60 shore A.

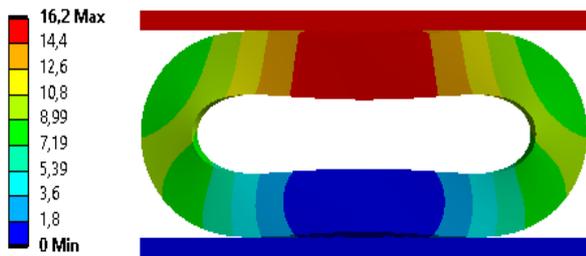


Figure 7A. TPU Cushion Displacement.

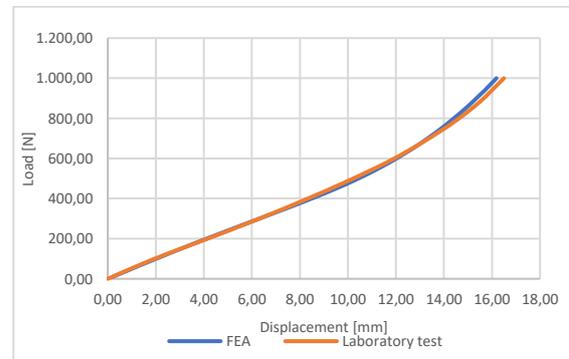


Figure 7B. Force VS Displacement for TPU pad.

Figure 8 presents a comparison between the numerical results for the rectangular natural rubber and the elliptical TPU cushion. It can be seen that the displacement for the elliptical TPU cushion is 2.8 mm greater than that for the natural rubber rectangular cushion.

By analysing the area under each curve, it is possible to obtain the absorbed energy for each cushion. The energy equation can be described as Eq. 3:

$$\int dW = \int \vec{F} dx,$$

where W , F and dx are the absorbed energy, the force and the displacement applied on the pad. The absorbed energy by the rectangular natural rubber and the TPU elliptical cushions were 6.7 J and 8.1 J respectively.

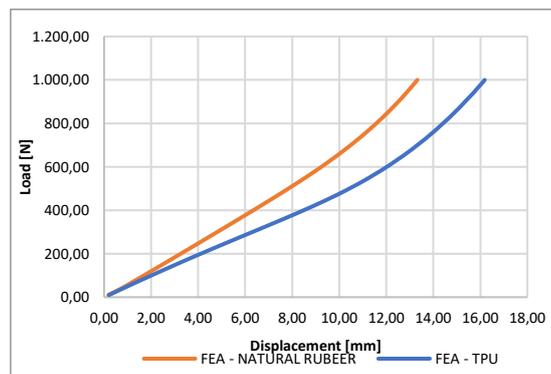


Figure 8. Comparison of Force VS displacement between Natural Rubber and TPU cushions.

4. DISCUSSION

The knee is the main joint in the lower limb and it is responsible for absorbing the impact during running or walking. To avoid injuries to it, a correct load transferring from the foot to the treadmill is imperative: it is thus necessary to design new and more efficient damping systems.

In a finite element analysis, which is widely used in the design of new equipment, simplifications are usually made to simplify a problem. However, such simplifications might not always result in an accurate analysis. In a damping system, for example, the geometry of the cushions plays an important role in their absorbing performance. In the majority of the models available in the literature, linear and simplistic spring and damper models often replace the actual geometry, resulting in non-realistic model predictions of the absorbing energy by the cushions (Hakanson, 2000).

By performing an analysis of the real component, it is possible to capture in detail the physical phenomena that occurs. In this study, the efficiency of each cushion in terms of absorbed energy and the influence of the geometry in their performance were analysed.

The Neo-Hookean constitutive model was used to represent the TPU elliptical cushion material behaviour. The material parameter was iteratively obtained by comparing the numerical results to the experimental. The value that met the convergence criterion for the Neo-Hookean constitutive model was 27.5 MPa.

According to Figure 6A, the 60 Shore A natural rubber cushion presents the largest displacement levels at the upper and central sections, next to the central hole. This was expected as the hole weakens the central portion of the cushion, resulting in a smaller stiffness when compared to other regions. In Figure 6B, it is possible to compare the results found in the experimental tests to the FEM model.

For the TPU elliptical cushion, Figure 7A and Figure 7B, the displacement gradient was uniform, as its oval shape and constant thickness and stiffness evenly distributed the load to the ground surface.

Comparatively, the experimental and numerical results were close for both cushions, presenting an error of 1.5% for the natural rubber cushion, and 1.9% for the TPU elliptical. This cushion presented an average elastic constant of 58.5 N/mm, resulting in 19% lower stiffness compared to the natural rubber cushion, which has an average elastic constant of 72.5 N/mm. As a result, the TPU elliptical cushion displaces more for the same applied force, absorbing more energy than the rectangular natural rubber cushion.

The TPU elliptical cushion has an impact absorption capacity of 8.1 J but it is 80% lighter than the natural rubber cushion, whose impact absorption capacity is 6.7 J. The absorbed energy levels found in the present study are higher than the results obtained by Chiu et. al (2007), which analysed the impact absorption capacity of sneakers, assessing values between 1.0 J and 6.0 J. According to Chiu (2000) values from 3-7 J represent the energy of a person exercising at 3 m / s.

Baltich et. Al (2015) study found that sneakers with a more rigid insole presented lower impact forces to the ground. Further studies must then be conducted to correctly understand the relationship between the ground reaction forces and the stiffness of the running pad.

5. CONCLUSION

In this study, the performance of two different models of cushions commercially used in treadmills was analysed in terms of absorbed energy using finite element models. Numerical models were created, based on real geometries, and validated against experimental data.

The finite element method was able to reproduce the mechanical behaviour of both cushion models. As the difference between numerical and experimental data was small, it was possible to obtain the energy absorption capacity for each component, which will support future optimisation studies of the cushion geometry.

The TPU elliptical cushion is more efficient compared to the rectangular natural rubber cushion: it has a greater impact absorption capacity and is lighter. Moreover, the TPU elliptical cushion is manufactured by an injection process, which is cheaper when compared to the vulcanization process for natural rubber, which makes this component more competitive for the application on treadmills.

In future studies, an optimisation analysis of the geometry of the cushion will be performed to obtain the cushion geometry that greatly reduces the impact loading, avoiding injuries and providing comfort to users. A sensitivity analysis will also be conducted to analyse the influence of the cushions on the overall performance of the treadmill in absorbing the impact from running or walking.

6. REFERENCES

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7. RESPONSIBILITY NOTICE

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