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Use of CAD software in developing mechatronic medical devices on example of Treadmill

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Abstract— **This paper presents using of a Computer Aided Design software as an aid in designing of modern mechatronical medical devices on an example of an infinite belt – Treadmill. In this paper the software SolidWorks was used, as a module for virtual design and modeling of 3D models of devices. Moreover, the SolidWorks Simulation, as an integral part of the SolidWorks software, was used for examination of the state of stress and strain in order to sizing constituent parts of the developed Treadmill device.**

Key words – Computer Aided Design; Treadmill; Finite Element Analysis; Sizing

I. INTRODUCTION

Infinite belts – ’’*Treadmills*’’, are devices for running and walking whereby user stays in one place. Invention of infinite belts is related for period before XIX century. There was one type of grinder, Treadwheel, which was driven by a man or an animal who was rotating a wheel in a form of a infinite belt, and on that way, grain were grinded. The idea of infinite belts was taken and used in designing of modern Treadmills.

Our research has shown that actually exist many types of these devices with different functions as: car Treadmills, Treadmills for training and examination of animals [1], training of sportsmen [2] etc. Certainly, the most important ones are medical devices that are used for examination of the heart work [3] of healthy and ill people. The invention of medical Treadmills is related to the need for gradual fatigue of a patient to monitor his heart rate during exercise or other stress, which leads to increased heart rate. The idea is that a patient is moving along an infinite belt that gradually accelerates and elevates over time. During the test, the patient is connected to the Electrocardiogram (ECG) unit that continuously measures the parameters of his heart and transmits them to a computer, which on the other hand commands the work of the device. The first devices of this type appeared in the middle of the XX century.

Designing of modern mechatronical medical devices [4, 5], for example of infinite belts, in small and medium enterprises is, beside the parameters which set the task of the projects, requirements of the dimensions of the device, control and ergonomics, more difficult because of requirements on the safety of constitutional mechanical and electrical components. The reason is reflected in the fact that medical devices criteria are stricter compared to those for commercial purposes. In current conditions, an additional problem is the impossibility of making more prototypes, so it is usually reduced to only one prototype. For that prototype it is impossible to be adequately examined in all possible situations that may occur during prolonged use in health care institutions. In order to solve these problems, in the process of designing, from the very beginning, it is very useful that modern software for developing a virtual prototype is included [6]. Using of this software reduces the total time required for the development of new products, as well as the price of the product itself, while it is possible to increase the level of product innovation as well. A virtual prototype is relatively quickly ready for a visual inspection, control sub-assemblies and components and for the final ergonomic evaluation. As this software allows the execution of simulations, which serve to simulate realistic conditions since the beginning of the design, the analysis is involved at different levels during the development process. In that way it is possible to examine the potential collisions of moving parts, carry out sizing of certain parts, calculate the required power train and so on. At the end, simulation of the stress state can be performed, in order to check whether the designed parts of the selected materials can withstand predicted loads, as well as their optimization according to adequate criteria, for example for minimizing the total mass.

The modern approach of computer aided design (CAD) of medical Treadmills includes conceptual and functional designing. The conceptual design determines the best conceptual solution of a Treadmill under the required conditions, while the functional designing includes processes like modeling of device’s parts, identification of possible problems that occur during the use of the device and verification whether the final product conforms to the designing requirements.

II. DESIGNING PROCESS

A systematic approach to the development of new modern mechatronical medical devices on an example of infinite belts - Treadmills was implemented in this paper. The core phases were:

1) Concept definition,

2) Modeling using CAD software,

3) Determination of forces necessary for the elevation movement of the Treadmill,

4) Stress simulation of particular Treadmill parts.

During the designing process of medical devices a different design philosophy should be followed in comparison with the fitness industry. This approach is focused on patient-centered design process and cardio requirements are prioritized in the concept development stage.

1) Concept definition phase

Based on reviews of current solutions and consultation with specialist from the cardiology field, parameters of the Treadmill were defined, the functions that should have be fulfilled and movements which had to be provided. Since there are two main movements in Treadmills, the planned structure of the developed device consists of the two subassemblies (Fig. 1). The first subassembly provides a continuous rotation of the infinite belt on which the patient walks (1), while the second one elevates the whole device (2) (changing the angle of inclination - elevation). It is adopted to use an actuator as a driving element for the elevation (an electromotor in conjunction with the screw spindle). Rotating of the infinite belt is provided by an electromotor which transfers movement via a belt drive to rollers around which the belt rotates. As the Treadmill during the work increases the rotation speed of the belt gradually, the tested patient has to accelerate his walk, which, in one moment, goes into running. It is well known that during running, there are moments when the body comes to state which is so-called "jump", i.e. the moment when both feet are in the air and the walking pad is released from the load. After that, repeated contact with the walking pad seeks to reduce the rotation speed, but more important for the test is appearing of unwanted vibrations, so-called "artifacts", which badly affect the operation of the ECG device leading to obtaining incorrect results. In order to solve these problems, it is adopted that the Treadmill device should have a special anti-vibration pad between the device's frame and the walking pad. In addition, the existence of security switch is adopted whose activation stops the movement of the belt. Moreover, the security switch can be activated by the patient if he feels the health difficulties, or a doctor, who performs testing, if he sees that patient's health parameters, which are received from ECG tests, indicate a problem in the heart work.

2) Modeling using CAD software

The embodiment involved CAD modeling in SolidWorks 2010 [7] and its functional units as a CAD module for virtual prototyping and modeling of three-dimensional parts and assemblies. Firstly, a mechanical part, which consists of many independent parts, has been modeled. Based on the theory of systems with many bodies (multibody) [8], the mechanical part of a system is defined as a set of bodies joined by joints that allow them to move rectilinear or rotary, depending on degrees of freedom that are limited or remained free [9].

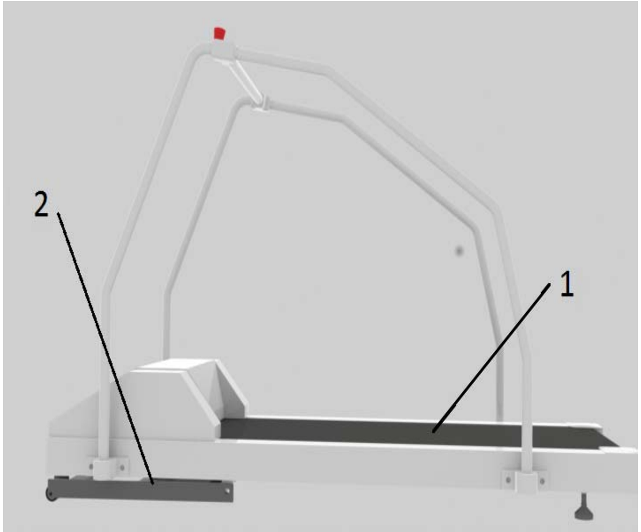

Fig. 1. The Conceptual design of the Treadmill

The mechanical part of the Treadmill assembly consists of two subassemblies (Fig. 1),. The First subassembly is the walking pad (1), representing the infinitive belt that rotates and on which the patient walks. The infinite belt is stretched over two rollers, where the front roller is in connection with motor through the belt drive. The second subassembly (2) is the elevation subassembly, which elevates the whole machine up to the angle of 25%, which is specified by American Medical Association [10]. This subassembly consists of a moving pad which is in connection with the platform on one side, and on the others side with an actuator, which elevate the machine. After the modeling process, the kinematic analysis has been performed on the model of the device. The aim of this analysis was to determine the movement of device's components, one in relation to another and to correct potential collisions between components. A complete assembly of the machine modeled and rendered in the SolidWorks software package is shown in Fig. 2.

Fig. 2. The assembly of the Treadmill

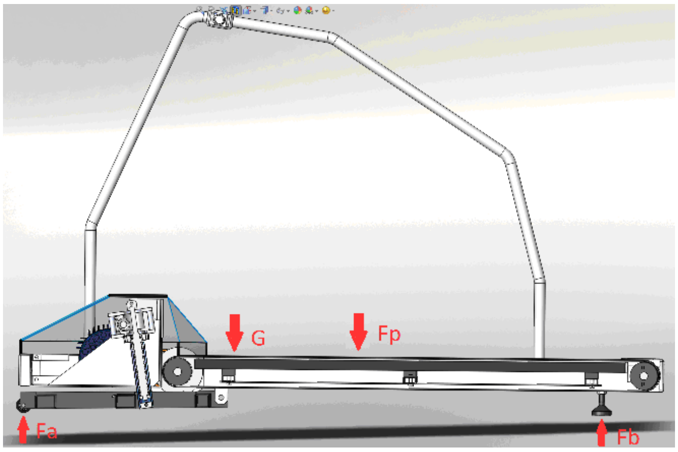

Fig. 3. Determination of the forces in the supports

3) Determination of forces necessary for the elevation movement of the Treadmill

Parts of the machine that are involved in the elevation process are actuator and the moving pad. In order to calculate the elevation movement, it is necessary to find the force with which the actuator should act on the moving pad. This force is very important for adequately sizing the actuator as well. To find this force, it is firstly necessary to calculate the forces in the supports (Fig. 3). At Fig. 3 the following notes are used:

- Fa and Fb are the forces in the supports of the machine that should be found,

- G is the resulting force from the weight of the machine,

- Fp is the resulting force from the weight of the patient. It is taken as the maximum value of 1500N as patients of more than 150-160kg are not suitable to be tested on Treadmills because of potential health risks.

For the static calculation the following equations are used:

$$\sum F : Fa + Fb = G + Fp \, ,$$

$$\sum M_B : \overline{AB} \cdot Fa = \overline{GB} \cdot G + \overline{PB} \cdot Fp \, .$$

When the forces in the supports were found, the force in the actuator was able to be found (Fig. 4). In a similar manner, using Varignon’s theorem:

$$\sum M_C : \overline{AC} \cdot Fa = F_{akt} \cdot \overline{AktC}$$

the force in the actuator was found. Its value was calculated on 5413N. The distance between point C and the direction perpendicular to the force Fakt is changing over time, as the elevation angle increases, ranging from 220mm to 190mm. As the greatest force in the actuator is required when the mentioned distance has the minimal value, the lowest limit of 190mm was used for the calculation. The elevation also leads to reduction of the forces of weight of the patient and machine, because they act at the elevation angle relative to the machine. Because of that, it was necessary to decompose theses forces into two components. However, normal components of these

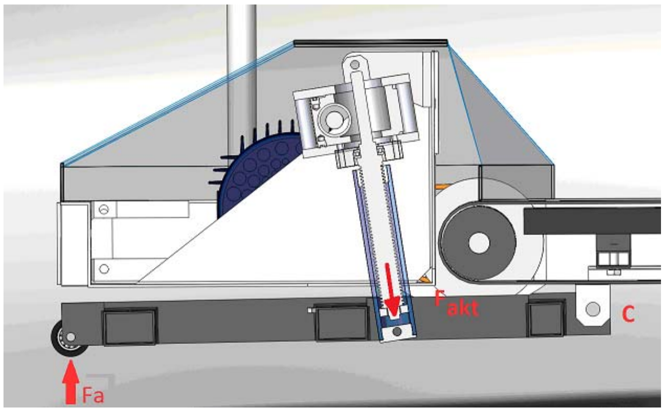

Fig.4 Determination of the force in the actuator

forces are not greater than the forces of weight of the machine and the patient, and the maximum elevation angle is not very large, the consequences of the elevation are not taken into consideration for calculating the force in the actuator. Finally, it was adopted that the force in the actuator is 5500N for easier use in the further calculation.

Based on this actuator force, other components which are parts of the actuator, like screw spindle, DC motor, reductor and so on, should have been calculated and adopted. Due to a specific maneuver space of the elevation assembly, any standard solutions for the actuator that were able to be found on the market, were not useful to be used. Therefore, it was necessary to build an own actuator. The actuator designed for this subassembly consists of the following parts:

- Upper and lower plate,
- Screw spindle,
- Carrier pipe,
- Axial bearing carrier,
- Axial bearing,
- Lower cap,
- Lower guide,
- Distant shells (four parts) and
- Nut.

The assembly of the actuator, modeled in SolidWorks is shown in Fig. 5.

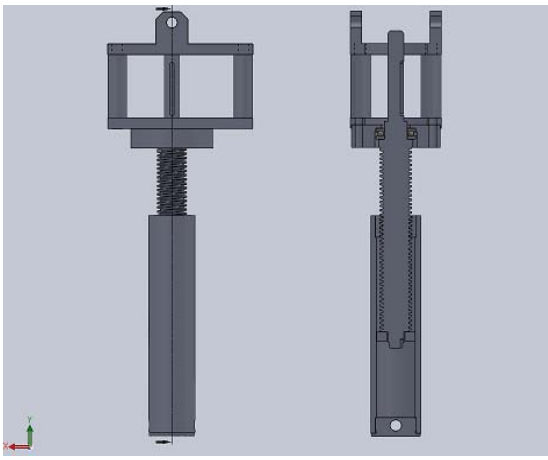

Fig. 5 Assembly of the actuator

4) Stress simulation of particular Treadmill parts

The SolidWorks software package supports the testing of parts and assemblies by using finite elements analysis (FEA) [10]. For the purpose of Treadmill parts sizing the stress simulation of all parts has been done, but for this occasion the stress simulation is shown on analyses of the elevation subassembly and actuator.

The main problem that arose because of the elevation movement was finding a sufficiently robust construction that was able to withstand patient's running on the Treadmill, in any of possible elevation positions, without damaging it. This problem was solved by adequate dimensioning of critical machine parts, which were tested by FEA analysis, to verify that the adopted technical solution and selected materials were able to withstand anticipated loads.

For simulations using FEA methods some parts of the whole machine that are going to be simulated should be separated. Otherwise, a simulation of the whole assembly may cause waste of computer resources and user's time. For this testing only elevation subassembly was considered in the simulation. For the analysis, restraints and loads were set firstly. In this case, because of the easier calculation, weight forces and reactive forces in supports were switched (Fig. 6; green arrows – restraint forces, violet arrows – active load). In the next step, materials were assigned. Finally, after meshing, the simulation was done.

Modern computers could perform this analysis in a short period of time regardless of the fact that the analyzed subassembly had over 240000 nodes and about 160000 elements. Simulation Von Misses results of FEA analysis of the elevation subassembly are given in Fig. 7 for the whole subassembly and Fig. 8 for the critical part of the subassembly.

The Von Misses results show that the maximum stress of the subassembly is 183.5MPa. This stress occurred on the pin which connects the actuator and moving pad. The material selected for the pin is steel Č1530 (C45 DIN equivalent) with yield strength of 275MPa, which means that the material choice and sizing of the pin were appropriate.

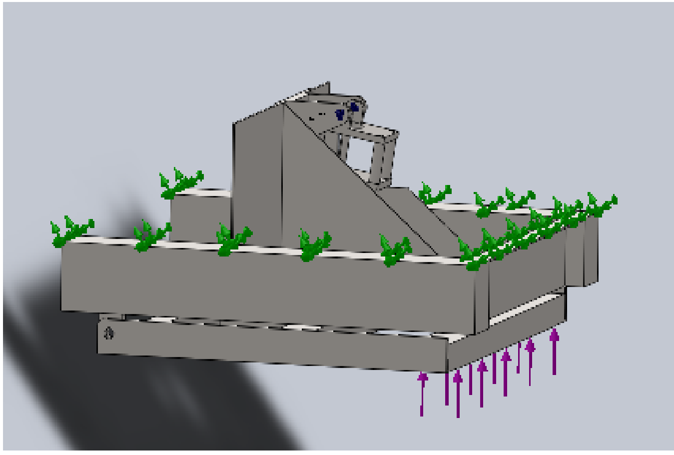

Fig. 6 Restraint and load of elevation subassembly

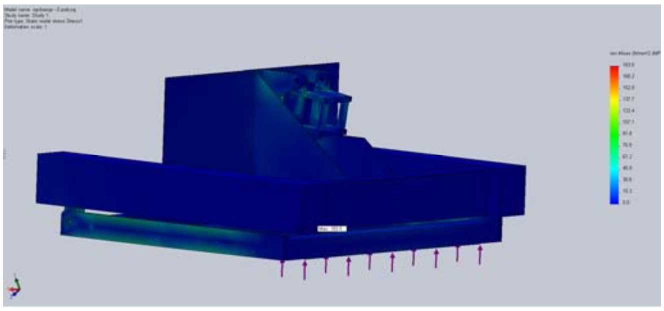

Fig. 7 Von Misses results of FEA analysis of the elevation subassemby (the whole subassembly)

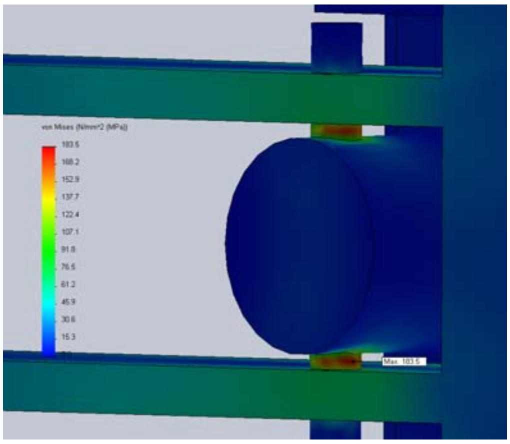

Fig. 8 Von Misses results of FEA analysis of the elevation subassemby (the critical part of the subassembly)

The second simulation was done for analyzing the actuator stress state. The actuator was loaded at the bottom with the force of 5500N, while on the top a fixed restraint was set (Fig 9). The Von Misses results of FEA analysis of the actuator show that the greatest stress occurs at the place of contact between the screw spindle and nut. The maximum stress is 68.8MPa, while the yield strength of the material selected for the actuator is again 275MPa (steel Č1530 (C45 DIN equivalent)), which means that the material choice and sizing of the actuator were appropriate.

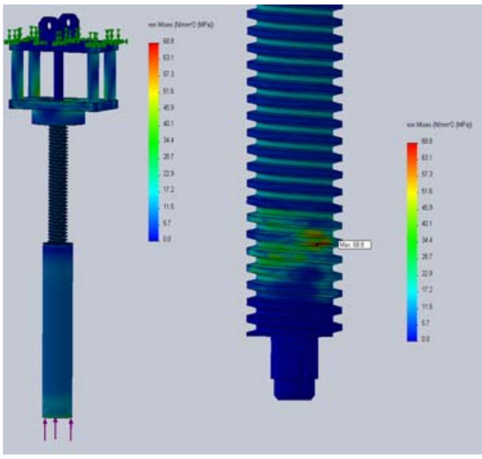

Fig. 9 Von Misses results of FEA analysis of the actuator

After successful designing process by using CAD software SolidWorks, conducting of FEA analysis and simulations and verification of the concept, a real mechatronical medical devices based on an infinite belt – Treadmill has been built (Fig. 10). This Treadmill is installed in a medical institution, where it serves as a major asset in diagnosis of heart diseases.

Fig. 10 Treadmill T02M

III. Conclusion

This paper apostrophizes the necessity of usage CAD software during designing processes of modern mechatronical medical devices. It is demonstrated on the example of the infinite belt devices – Treadmills that are used for medical purposes as an aid during ECG tests. For obtaining accurate results during complex medical analyses, it is necessary to construct robust Treadmill devices in which vibrations are minimized. The usage of CAD software allowed us during the designing of the developed Treadmill T02M creating the virtual prototype on which visual inspection was performed, possible collisions between moving parts were corrected, forces, torques and so on were measured and checked. These saved a lot of resources and time, because it was not necessary to build any real physical models up to the final time of producing the real prototype. During simulations of the virtual prototype, defects of certain technical solutions and selected materials can be also analyzed and corrected on time, which results in more economical and efficient products. Finally we can conclude that the approach presented in this paper, using CAD software for designing process of modern mechatronical medical devices, results in advantages of contributing to reducing the price of products, reducing development time and improving overall product quality which is especially important for the medical devices.

Acknowledgements

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