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MODELLING OF THE CONTROL SYSTEM OF A TRANSFEMORAL PROSTHESIS OF THE HUMAN LOWER LIMB

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In this work considers current problems of modern medicine and rehabilitation, which are based on the development of automated systems with the ability to control transfemoral lower limb prostheses.

This is one of the most complex problems that perform the necessary tasks associated with the study of the features of the construction of prosthetic structures, used materials, and combinations, which affects the ultimate reliability and functionality of these devices.

The paper analyzes the methods of ensuring the operation of an automated transfemoral prosthesis with the aim of further optimizing the main characteristics of the control system. Thus, some of the most important parameters of the system are considered, which are designed to ensure improved reliability and durability of the prostheses, increase the level of comfort of daily use, use of light and durable materials, and improve the interaction between the prosthesis and the user.

Thus, the conducted studies of the strength resource of the prosthesis are intended for further optimization of its weight according to minimization criteria. Based on the conducted studies of the analysis of load distribution in the prosthetic transfemoral part of the lower limb, parameters for minimizing the mass of the prosthesis part while maintaining its strength are proposed, and the results of the study of frames are presented.

The results of modelling the optimization of an automated control system for transfemoral prostheses taking into account gait defects are presented in order to select parameters that improve the operation of such prostheses, taking into account the design and psychological aspects of their application.

The authors of this work consider promising areas of research to be optimization of control algorithms for the automated prosthesis system, since these approaches also allow for correction of the trajectory and speed of movement, and the patient's maneuverability in a defined workspace.

Keywords: *transfemoral prosthesis; lower limb; control system's; optimization; automated prosthesis system.*

Introduction

Modern global challenges that have arisen as a result of military operations, associated with the presence of severe injuries, in particular the loss of normal functioning of limbs, require the use of automated technical devices and systems that help the patient restore the ability to move [1]. In addition, severe infectious diseases that accompany the existing conditions of human life, some types of injuries and the general circumstances of human existence in war conditions, lead to severe psychological stress, which leads to disorders of the nervous system with the loss of normal movement.

This paper focuses on one of the most severe and common cases of amputation, namely transfemoral amputation.

The creation of transfemoral prostheses of the lower limbs of a high level of amputation is a separate rather difficult task. In this case, it is critically important to have a control system to simulate movements that could be performed naturally [2, 3]. This includes dynamic adjustment based on data on load, position, speed and other physiological parameters .

Modelling the control system of an automated transfemoral prosthesis of the lower limb is an extremely important modern problem, which can actually be performed on the basis of a combination of tasks of biomechanics, robotics, medicine and engineering, that is, the actual formation of an automated mechatronic system. It is important to determine the features of creating modern transfemoral prostheses, optimizing the parameters of the control system necessary for the effective functioning of these devices.

Therefore, the purpose of this work is to model the control system necessary to optimize the design of an automated transfemoral prosthesis taking into account human anatomical features.

If you choose the wrong length of the main elements of the prosthesis, this can lead to gait defects, stump injuries and posture problems. Of course, it is necessary to take into account that people are different from each other. Therefore, it is necessary to establish the range of sizes of the main parts of the leg (thigh, lower leg, foot), and establish their average value. At the same time, it is necessary to take into account the sexual dimorphism inherent in people, which will give a slightly different range of lengths depending on the sex of the person. The assessment of the length of the parts of the leg is carried out based on the length of the main bones [4, 5, 6].

In order of the purpose of this work, it is necessary to review the technical solutions available in other studies regarding the transfemoral prosthesis control system.

Analysis of existing solutions for restoring knee function for people with transfemoral amputation

All prostheses are divided into two types according to the principle of operation: mechanical and automated (computerized).

In addition to the division into mechanical and computerized, such prostheses can also be divided by the number of axes. One of the first transfemoral prostheses was a leg imitation with a uniaxial knee joint. Such a simplistic solution is still used even in some computerized models [3], uniaxial prosthesis from Medical Expo with manual knee fixation (Fig.1) [7]. There is also a variant of "safe" uniaxial knee joints, the principle of which is built entirely around a special friction mechanism. An example of such a prosthesis is the Endolite Phoenix prosthesis, shown in Fig. 2 [7].

Fig. 1. Uniaxial prosthesis from Medical Expo with manual knee fixation [7]

Fig. 2. Uniaxial prosthesis Endolite Phoenix with load fixation [13]

To solve the problems that arise when using single-axis prostheses, computerized automation and variable dampers are used. These systems are able to dynamically adapt to different movements and their speed. They are the ones that are able to most closely approximate the experience of using a prosthesis to using a healthy limb. By assessing the state of the components relative to the environment and each other, this prosthesis is able to correctly model kinematics and respond to changes in a timely manner.

A good example of a computerized uniaxial prosthesis with a variable hydraulic damper is the C-Leg from Ottoblock, shown in Fig. 3 [7].

Another case is multi-axis knee joints. These systems usually consist of 4 axes, which in the extended state shift the center in such a way as to prevent spontaneous bending. If necessary, this connection bends easily, so it is quite convenient to use [8].

A fairly common control method is control by fixed input parameters. Such control systems are considered in the works [9], [10], [11]. Their principle of operation is to respond to clear parameters and change them according to a certain algorithm or function.

Fig. 3. Uniaxial computerized C-Leg prosthesis from the Ottoblock company [7]

This is one of the most common ways to control the knee mechanism. It does not require a significant amount of computing power and is reliable in direct use. According to certain movements, the system will behave in a clear, programmed way. Such control systems can be built either conditioned by clear values [12], or such that will fix the more general trend of movements and adjust to it [12, 13, 14]. In both cases, most often, such solutions are used to fix the phases of gait [9], [10], [11].

Such control systems have clear disadvantages, such as inflexibility and long setup time. Due to the dependence on certain clear parameters, such systems cannot simply adapt to various gait deviations or non-standard movements. Such nuances must be taken into account during the direct development of the software. This, in turn, poses the problem of long-term adjustment of such systems to the individual characteristics of the patient. Therefore, it is worth choosing a prosthesis that will include an automated control system, and optimizing the design, control system and sensor system.

Materials and methods

Taking into account the anthropometric parameters of the leg, the features of the amputation and the technological solutions used in the creation of transfemoral prostheses, you can proceed to the selection of the desired design of a single-axis computerized knee prosthesis.

The work proposes an automated uniaxial knee mechanism built on the basis of a variable liquid damper (Fig. 4).

Based on the research conducted, the mechanical and electrical parts of the prosthesis of the proposed automated knee mechanism was improved.

Given the shortcomings of the old damper, the problem of choosing a new shock absorber for the prosthesis arises. Taking into account the high loads during walking and other activities, the variable damper must be able to withstand the applied loads up to 2000 N, have dimensions within ∅50×300 mm and have high speed for dynamic adaptation to human movements.

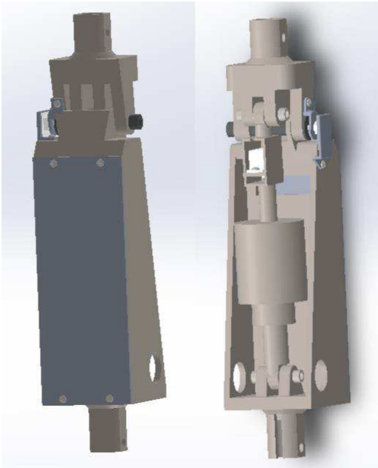


Fig. 4. View of the proposed automated knee mechanism of a transfemoral prosthesis

Variable dampers with magnetic fluid are devices that can change their stiffness or damping properties in real time under the influence of a magnetic field. Their main working medium is a magnetorheological fluid — a suspension of microscopic ferromagnetic particles evenly distributed in a viscous base. In the normal state, such a fluid behaves like a regular fluid, but under the influence of an external magnetic field, its viscosity increases sharply, turning it into almost a solid material. This allows you to accurately and quickly change the degree of damping or resistance in mechanical systems. The variability of the characteristics is provided by an electronic controller that regulates the current strength in the piston winding, and therefore the strength of the magnetic field. The advantages of this technology are speed, accuracy of adjustment and the absence of complex mechanical switches.

The above requirements for damper parameters are met by the Bohai C series of interchangeable dampers. This series has a large number of dampers that differ in design, dimensions and load limits [15]. In addition, their dampers are distinguished by a response time of 15 ms, low power consumption, an operating temperature range of -20°C - 90°C and durability [15].

Taking into account the decisions made and the features of the prosthesis geometry, it was decided to divide the knee axis into two parts, on both sides of the replaceable shock absorber. In turn, taking into account the problem with axis abrasion in the previous design, a new solution was proposed, which is based on the use of rolling bearings, namely tapered roller bearings.

The use of tapered roller bearings in the design of the knee segment of a transfemoral prosthesis is advisable due to their ability to simultaneously withstand radial and axial loads, which is especially important for simulating the complex biomechanics of the knee joint. During walking, a significant load is transmitted to the prosthesis not only vertically, but also at an angle, due to the displacement of the center of mass, inertial forces and moments. Tapered roller bearings have a geometry that allows such complex loads to be distributed evenly across the contact surface, reducing wear and increasing structural stability. This is critically important for user comfort, joint reliability and long-term service life of the prosthesis. In addition, the ability to adjust the tension in such bearings allows you to fine-tune the mechanics of knee movement to the individual characteristics of the patient.

In the new design, the axles, provided the diameter is increased, are installed stationary, being hot-pressed into the femoral half of the knee joint. In turn, tapered roller bearings FLT 30204 A are pressed into special holes in the lower leg part. Thus, a reliable mechanism has been obtained that does not use friction in its rotation and is very wear-resistant and durable.

It is proposed that the frame of the lower leg part of the knee mechanism will be divided into six separate parts and welded at the seams (Fig. 5). In a similar way, the upper frame of the knee mechanism Fig. 6.

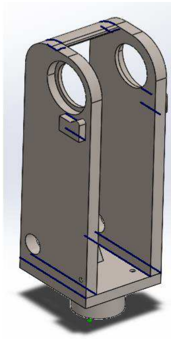


Fig. 5. Demonstration of the location of the lower leg part's welding seams

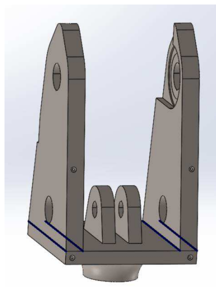


Fig. 6. Demonstration of the location of the femoral part of the knee mechanism's welding seams

Exploded elements of the frame of the lower leg part and the femoral part of the knee are showed at Fig. 7, Fig. 8.

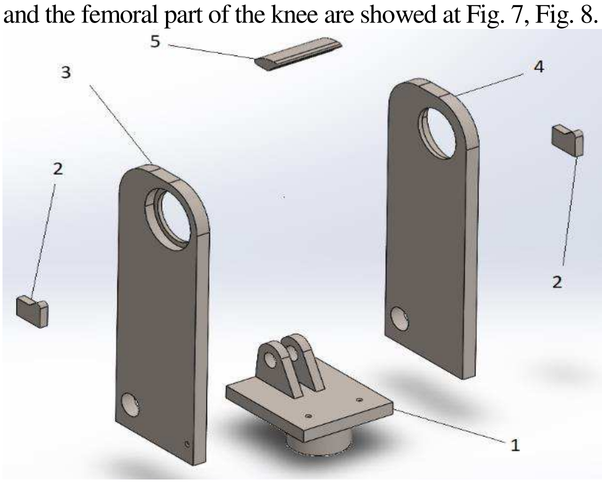


Fig. 7. Exploded elements of the frame of the lower leg part of the knee: 1 - base, 2 - stops, 3 - bearing plate, 4 - bearing plate, 5 – membrane

In addition, a different strain gauge sensor, such as FSR-402 [17], and a different element base of the sensor system and control system were selected. The result of the proposed optimized system is shown in Fig. 9 [12].

In the case of improving the knee mechanism, it is necessary to rely on the performance of the GY-521 modules [18] in the automated control system.

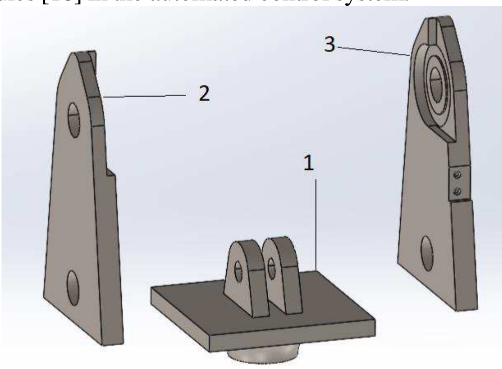


Fig. 8. Demonstration of the exploded elements of the femoral knee frame: 1 - base, 2 - support plate, 3 - support plate

After the changes made, the knee mechanism, including the damper and bearings, will look as shown in Fig. 10.

Based on the new transfemoral prosthesis control mechanism, an improved control system based on Arduino Nano was developed (Fig. 11) [16].

The GY-521 is a miniature module that contains a six-axis inertial sensor MPU-6050, which includes a 3-axis gyroscope and a 3-axis accelerometer [18]. Thanks to the built-in 16-bit ADC for each channel, it is able to accurately measure acceleration and angular velocities in three spatial directions, which makes it useful in robotics, game controllers, drones, stabilization systems and biomechanics.

The module is based on the MPU-6050 from InvenSense, which allows reading data from the accelerometer within ±2g, ±4g, ±8g and ±16g, and from the gyroscope - within ±250, ±500, ±1000 and ±2000 degrees/s. This allows you to adjust the sensitivity depending on the operating conditions. Data can be read via the I2C interface, which allows easy connection to most microcontrollers, including Arduino, STM32, ESP, etc.

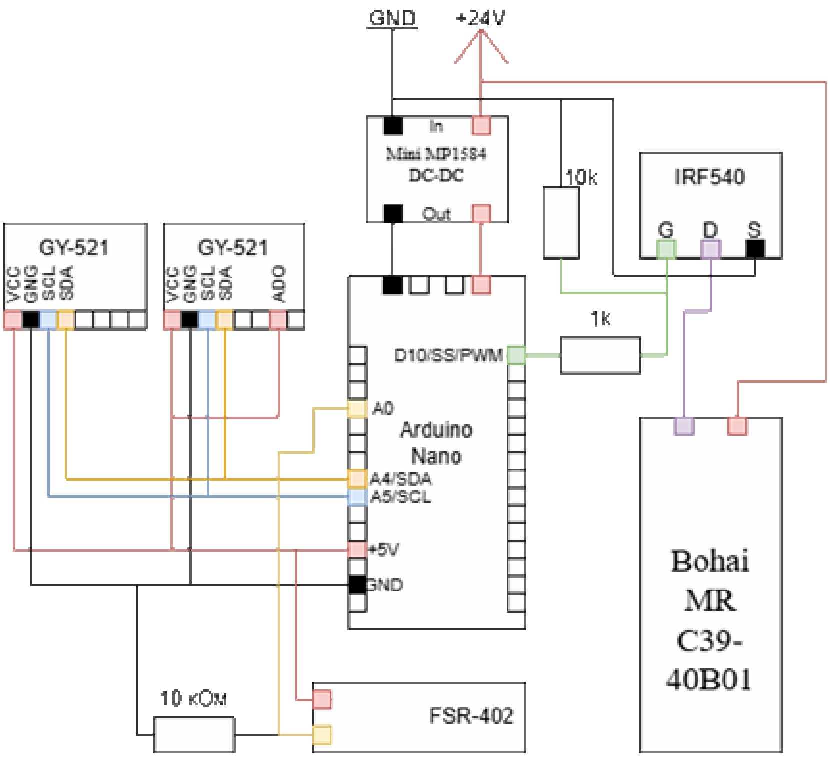


Fig. 9. Connection diagram of the control system and the sensor system [12]

Research results

To perform this study, we will use the Topology study function in Solidworks Simulation. Topology Study is a type of calculation that allows you to perform topological optimization, that is, find the optimal shape of a part that provides minimal weight while maintaining a given stiffness or strength. It is a powerful tool that imitates the "remove the excess" approach and is widely used in aviation, biomechanics, automotive, and 3D printing.

The essence of the method is that the user specifies the initial geometry, applied loads, boundary conditions, material, and optimization criteria - for example, reduce the mass by 50% while providing a given stiffness. After the calculation, the system determines which parts of the material can be removed without losing functionality, and generates a material density map or recommends a modified shape.

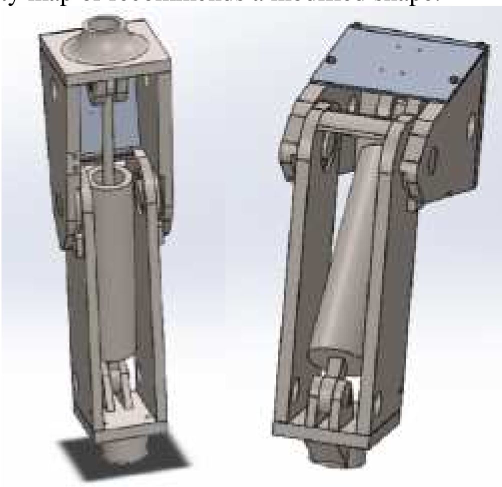


Fig. 10 The assembled mechanical part of the optimized knee mechanism

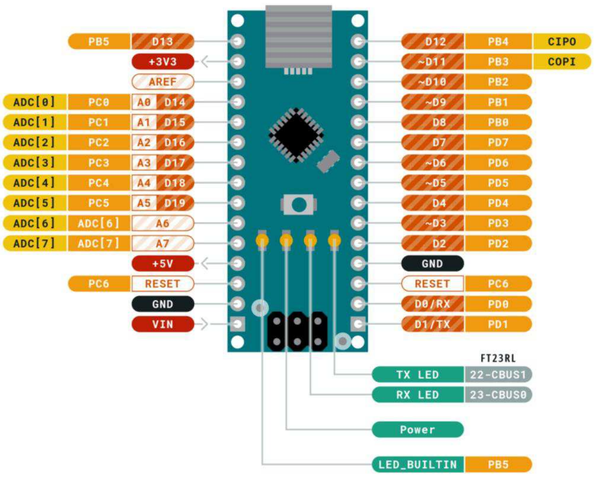


Fig. 11. Port locations and names [16] were used.

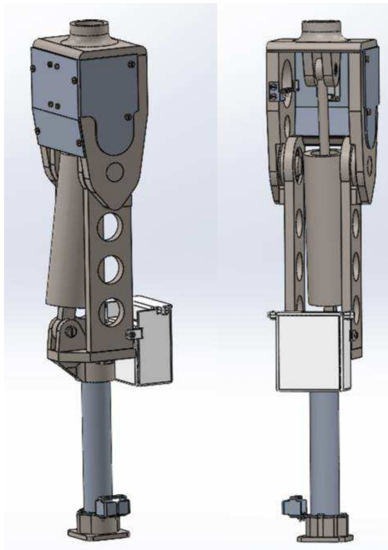
The result is a bubble-like structure that is unsuitable for traditional milling, but ideal for 3D printing. After the analysis is complete, SolidWorks allows you to export the geometry as a mesh or convert it to a solid model for further processing or verification using classic FEA.

Thus, using Topology Study, you can optimize the weight parameters of the heaviest parts of the structure. To obtain a practically satisfactory result, the study should be carried out three times using different load distributions. This will allow a synthesis of the obtained results and a model to be constructed that will be able to withstand the load in different positions.

A similar study was then carried out for the upper frame of the knee mechanism. Based on topological studies, it was decided to reduce the mass of the parts by removing a significant amount of material from the center of the support plates of both parts. This solution is the most stable. Also, according to the study, a small amount of excess material was removed from the edges of the support plates. The dimensions were also reduced and unnecessary corners were removed for the bases of the upper and lower frames.

Optimized design of the lower (A) and upper (B) frames of the artificial knee joint is shown at Fig.12.

So, the sensors, microprocessor and battery are installed on two separate plastic bases. These two bases are separately welded above the knee and ankle joints of the human leg. The GY-521 sensors must be located so that the X axis, depicted on the board, is directed towards the knee and the Y axis towards the toe of the foot.



A B

Fig. 12. Optimized design of the lower (A) and upper (B) frames of the artificial knee joint

On the bases, the sensors are located so that when standing they are parallel to the ground. The Arduino nano board is located on the one above the knee. There is also a nine-volt battery and a Bluetooth module HC-05. The gyroscopes and microprocessor are connected to the body with bolts. In turn, the battery and HC-05 are installed in a special cell on the base, and are fixed with adhesive tape and fixed on the leg with tape.

An image of the working prototype and its location on a human leg is shown in Fig. 13 and Fig. 14.

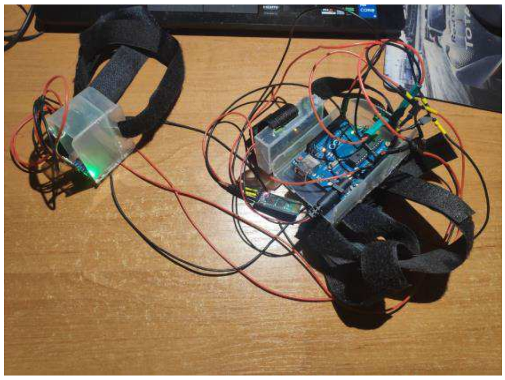


Fig. 13. An image of the working prototype

Based on the developed electrical circuit, it was decided to create a prototype of a sensor system for the study of gait defects, and further development of the control system.

A review of additional elements that will be used in the prototype was conducted. Based on the selected parts, a new basic electrical circuit was created. For this sensor system, programs were created for reading, processing and saving data on a personal computer. A method was developed for installing a prototype of a sensor system on a human leg, and, in accordance with the above, a prototype was created, which was tested in laboratory conditions of research.

Fig. 14. Image of the location of the working prototype on the human leg

Using the sensor system, a study was conducted of the dynamics of changes in the angles of inclination of the lower leg and thigh during defective gait.

Conclusions

The work analyzes the methods of ensuring the operation of an automated transfemoral prosthesis with the aim of further optimizing the main characteristics of the control system.

The weight of the frame parts was optimized while maintaining their strength and durability. As a result of the optimization, the total weight of the prosthesis was reduced by 34%.

A detailed assessment of the product's electrical system was performed and a schematic diagram of the control system and sensor system was created.

Thus, some of the most important parameters of the system are considered, which are designed to ensure improved reliability and durability of the prostheses, increase the level of comfort of daily use, use of light and durable materials, and improve the interaction between the prosthesis and the user. Using the optimazed system, a study was conducted of the dynamics of changes in the angles of inclination of the lower leg and thigh during defective gait.

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МОДЕЛЮВАННЯ СИСТЕМИ КЕРУВАННЯ ТРАНСФЕМОРАЛЬНИМ ПРОТЕЗОМ НИЖНЬОЇ КІНЦІВКИ ЛЮДИНИ

У цій роботі розглядаються актуальні проблеми сучасної медицини та реабілітації, які базуються на розробці автоматизованих систем з можливістю керування трансфеморальними протезами нижніх кінцівок.
Це одна з найскладніших проблем, що виконує необхідні завдання, пов'язані з вивченням особливостей конструкції протезних конструкцій, використовуваних матеріалів та їх комбінацій, що впливає на кінцеву надійність та функціональність цих пристроїв.
У статті аналізуються методи забезпечення роботи автоматизованого трансфеморального протеза з метою подальшої оптимізації основних характеристик системи керування. Таким чином, розглядаються деякі найважливіші параметри системи, які покликані забезпечити підвищення надійності та довговічності протезів, підвищення рівня комфорту щоденного використання, використання легких та міцних матеріалів, а також покращення взаємодії між протезом та користувачем.
Проведені дослідження ресурсу міцності протеза спрямовані на подальшу оптимізацію його ваги за критеріями мінімізації. На основі проведених досліджень аналізу розподілу навантаження в протезі трансфеморальної частини нижньої кінцівки запропоновано параметри мінімізації маси протезної частини при збереженні її міцності, а також представлено результати дослідження каркасів.
Представлено результати моделювання оптимізації автоматизованої системи керування трансфеморальними протезами з урахуванням дефектів ходи з метою вибору параметрів, що покращують роботу таких протезів, враховуючи конструктивні та психологічні аспекти їх застосування.
За допомогою оптимізованої системи було проведено дослідження динаміки зміни кутів нахилу гомілки та стегна під час дефектної ходи.
Автори цієї роботи вважають перспективними напрямками досліджень оптимізацію алгоритмів керування автоматизованою системою протезування, оскільки ці підходи також дозволяють коригувати траєкторію та швидкість руху, а також маневреність пацієнта у визначеному робочому просторі.
Ключові слова: трансфеморальний протез; нижня кінцівка; системи керування; оптимізація; автоматизована система протезування.

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