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DETERMINATION OF THE INFLUENCE OF THE TAPE TENSION AND THE DETACHMENT FORCE OF THE VELCRO FASTENER IN THE REHABILITATION FOOTWEAR

Об'єктом дослідження є конструктивні параметри ортопедичного післяопераційного взуття, що базуються на комплексних теоретичних та експериментальних дослідженнях впливу верхньої зовнішньої поверхні стопи на верх взуття при експлуатації. Одним з найбільш проблемних місць є недостатня виченість умов взаємодії черезпід'ємних ременів з застібною «велькро» та зовнішньою частиною халяви. Це необхідно задля забезпечення експлуатаційної надійності взуття.

В ході дослідження використовувалися графічні залежності зміни сили тиску на верхню частину післяопераційного ортопедичного взуття при згинанні підошви, як функції кута нахилу між дотичною до підошви взуття до площі опори. Визначено сили навантаження R на верх післяопераційного ортопедичного взуття, не враховуючи сили тертя між боковими поверхнями халяв та зовнішніми боковими сторонами ступні. В даному випадку задача зведена до складання рівнянь рівноваги плоскої системи сил.

Як показує практика експлуатації застібки «велькро», при збільшенні натягу опорної стрічки (з петлями) сила від'єднання на початку збільшується до деякого максимуму, а далі при зростанні натягу сила від'єднання зменшується практично до нуля. Ця обставина може впливати на зменшення надійності з'єднання халяв ортопедичного взуття. Для забезпечення міцності кріплення необхідно правильно обрати тип застібки, ширину та довжину активної зони зчеплення, щільність розташування гачків, що забезпечить надійність застібки у взуття.

Отримано оптимальні конструктивні особливості та найбільше значення сили тиску на верхню частину післяопераційного взуття при згині підошви, яку спостерігають при куті $\gamma = 25^\circ$. Це пов'язано з тим, що запропонований матеріал має ряд особливостей, зокрема хорошу щільність гачків на 1 см^2 .

Ключові слова: застібка «велькро», зчеплення черезпід'ємних ременів, натяг опорної стрічки, розташування гачків, згин підошви.

1. Introduction

Postoperative footwear is large enough to allow for a more bulky bandage after surgery. It can be worn temporarily while recovering from surgery or foot injuries [1]. The rigid sole allows, almost without bending the sole, to hold the foot without movement. Depending on the model, this type of footwear may be laced or a Velcro fastener is used.

Rehabilitation footwear is designed to be worn after the operation of the foot, the shoe has a durable soft top and is secured with a Velcro fastener to adjust the bandaged leg to a comfortable movement. In the process of restoring or compensating for dysfunctions of the musculoskeletal system in the foot area, the top blank has the ability to take the form of the patient's foot.

It is obvious that the main element that ensures the integrity of the design of shoes in the operating conditions is the Velcro fastener. During operation, the force of the external surface of the foot will act on the fasteners. To ensure the fastening of fasteners, it is necessary to choose the correct type of fastener, the width and length of the active area of the contact, the density of the hooks. In the event of a disruption of the contact by the supporting belt with the surface of the freebie, the structure itself will collapse. Therefore, it is possible to assume that theoretical

and experimental studies of the conditions of interaction between the front-supporting belts with a Velcro fastener with the external part of the freebies are relevant and have practical significance from the point of view of ensuring operational reliability.

2. The object of research and its technological audit

The object of research is the design parameters of the orthopedic postoperative footwear, based on complex theoretical and practical studies, namely the influence of the upper outer surface of the foot on the top of the shoe during operation.

Fig. 1 shows the power load on the sole and top of the shoe when bending the foot when walking. The method of liberation from bonds is used when compiling these schemes [2, 3].

Fig. 1 shows the value:

- l_R – the length of the welt of the shoe to the fold line of the sole, which is located from the edge of the heel of the shoe to the point of the internal flat-phalangeal joint;
- P – force is equal in magnitude and oppositely directed resultant of the distributed load;

- R – the pressure force on the upper part of the postoperative orthopedic shoe when the sole is bent;
- N – a normal reaction from the heel side to the inner surface of the shoe upper;
- kN – friction force between the heel and the inner surface of the shoe;
- k – friction coefficient between the heel and the shoe material;
- R_1, R_2 – friction forces between the lateral surfaces of the tops and the outer lateral sides of the foot.

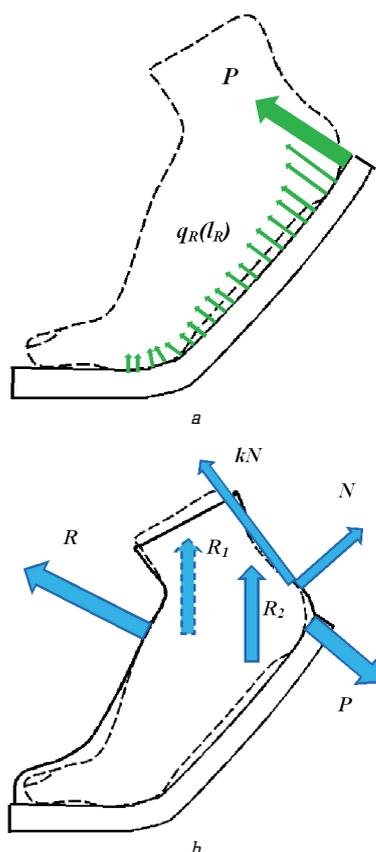


Fig. 1. Power load schemes: *a* – on the sole; *b* – on top of the shoe

One of the most problematic places is the insufficient knowledge of the conditions of interaction between the supporting belts with the Velcro fastener and the outer part of the freebies, which is necessary to ensure the operational reliability of the shoes.

3. The aim and objectives of research

The aim of research is obtaining the mathematical dependencies to determine the forces acting on the top of the shoe during operation. The use of these dependencies, at the design stage of the design of orthopedic and postoperative shoes, will allow to choose a design with a supporting belt.

To achieve this aim it is necessary to perform the following objectives:

1. To determine the distributive load on the sole, the friction forces between the lateral surfaces of the tops and the outer lateral sides of the foot, the friction coefficients of the foot with the material, the moment of inertia of the sole section.

2. To make an analysis of graphic dependences of the value of the pressure force on the upper part of the postoperative orthopedic shoe when bending the sole.

3. To determine the force of detachment of the tape with loops with increasing tension of the supporting tape and with its growth.

4. Research of existing solutions of the problem

Among the main directions of solving the calculation of the design parameters of orthopedic and postoperative footwear, identified in the resources of the world scientific periodicals, can be highlighted [2, 3]. But they did not consider complex theoretical and experimental studies of the influence of the upper outer surface of the foot on the top of the shoe during movement.

The work [4] is devoted to the design of orthopedic shoes, taking into account the nosological features of the feet of people, however, there is an unresolved question of mathematical calculations of the load on the parts in the shoes.

Testing the completeness of the shoe, the stability of the shoe volume to heat, and methods for testing materials on the shoe are specified in [5]. However, this work does not fully address the issues of determining materials for the manufacture of sustainable textile fasteners in orthopedic shoes.

The authors of [6] show the dependence of the fastener width, the density and height of its hooks, but the question remains about the width and length of the fastener depending on the thickness of the hooks, to ensure the durability of fastening the shoes on the foot.

An alternative solution to the problem of fixing shoes on the foot with the help of tapes with hooks described in the study [7], which does not provide for determining the number of hooks per 1 cm^2 , as well as a graphical dependence of the density of hooks per 1 cm^2 .

The authors of [8] in their study show a variety of fastening parts of the top in orthopedic postoperative shoes. The authors of the work [9] investigate the fastening strength of fasteners, for which it is necessary to choose the correct type of fastener, the width and length of the active grip area, the density of the hooks.

In [10], the calculation of design parameters is considered, which emphasizes practical importance from the point of view of ensuring operational reliability of shoes, and in [11] the importance of constructing graphical dependencies of pressure force variation in shoes is emphasized.

Thus, the results of the analysis allow to conclude that in the case of adhesion disruption of the supporting belts to the surface of the freebie, the structure will collapse as such. As well as the fact that the method of fastening the shoes on the foot with the help of the Velcro fastener and the strength of the connection of the hooks of the fastener to each other depending on its parameters remain insufficiently studied.

5. Methods of research

The distributed load (Fig. 1, *a*) on the sole $q_R(l_R)$ is replaced by the resultant force P' , which is determined by the formula:

$$P' = \int_0^{l_R} q_R(l_R) dl_R, \quad (1)$$

where l_R – the length of the welt of the shoe to the fold line of the sole, which is located from the edge of the heel of the shoe to the point of the internal flat-phalangeal joint.

The following forces act on the upper part of the post-operative orthopedic shoes:

P – force, equal in magnitude and oppositely directed resultant of the distributed load;

R – force of pressure on the upper part of the post-operative orthopedic shoe when the sole is bent;

N – normal reaction from the heel to the inner surface of the shoe upper;

kN – friction force between the heel and the inner surface of the shoe;

k – friction coefficient between the heel and the shoe material;

R_1, R_2 – friction forces between the lateral surfaces of the tops and the outer lateral sides of the foot, which are determined by the formulas:

$$R_1 = \int_0^{s_1} k_1 q_1(s_1) ds_1, \quad R_2 = \int_0^{s_2} k_2 q_2(s_2) ds_2, \quad (2)$$

where s_1, s_2 – lateral areas of contact of the tops with the outer and inner sides of the foot; k_1, k_2 – friction coefficients between the outer and inner sides of the foot and the material of the tops (under the conditions of the problem under consideration, we can take $k=k_1=k_2$); $q_1(s_1), q_2(s_2)$ – the distributed normal pressure between the outer and inner sides of the foot and the leg material.

To determine the resultant force P' (Fig. 1, a), it is necessary to write an equation that relates the dependence of the bending moment on the curvature of the sole axis.

For the conditions of the considered problem, it has the form:

$$\frac{1}{\rho} = \frac{P'}{EI_x} L, \quad (3)$$

where P' – the bending force; E – elasticity modulus of the sole material under tension (for porous rubber, its value is equal to 50÷500N/cm²); I_x – the moment of inertia of the sole section relative to the x axis, perpendicular to the central axis of the sole; ρ – radius of sole curvature in the zone of contact with the metatarsophalangeal joint; L – shoulder of the bending forces (the distance from the edge of the heel shoes to the fold line of the sole – is assumed to be equal to 0.67 of the foot length).

The moment of inertia of the sole section relative to the x axis (Fig. 2) [4] can be determined by the formula:

$$I_x = \frac{ba^3}{12}, \quad (4)$$

where a, b – the geometric dimensions of the sole section.

Solving together (3) and (4) let's obtain the formula for determining the resultant force P , with which the sole at the bend will act on the upper part of the shoe:

$$P = P' = \frac{EI_x}{\rho L} = \frac{Eba^3}{12\rho L}. \quad (5)$$

To determine the load force R on the top of the post-operative orthopedic shoe, one can neglect the friction forces between the lateral surfaces of the tops and the outer lateral sides of the foot. Thus, the task will be reduced to the compilation of equilibrium equations for a flat system of forces.

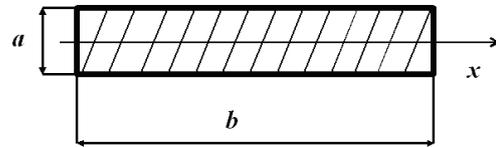


Fig. 2. The shape of the cross section of the shoe sole: a, b – the geometric dimensions of the cross section of the sole

Fig. 3 shows the design scheme. In this scheme, individual sections of the shoes are replaced by corresponding geometric images. This is done to simplify the determination of the required geometric characteristics, the inclination angles of the force vectors.

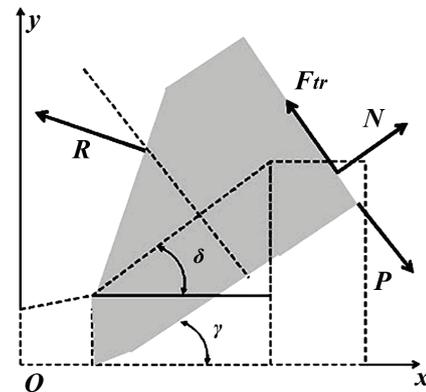


Fig. 3. The design diagram of the load of the top of the shoe

In Fig. 3:

- δ – the angle characterizing the slope of the foot and covering its tops;
- γ – the inclination angle between the tangent to the sole of the postoperative orthopedic footwear of the support plane (may be in the range of 200÷400, usually taken to be 250);
- R – the pressure force on the upper part of the postoperative orthopedic shoe when the sole is bent;
- N – heel pressure on the surface of the shoe;
- P – the resultant force with which the sole at a bend will act on the upper part of the shoe.

As can be seen from the diagram in Fig. 3, there is a flat arbitrarily located system of forces. To determine the unknown forces, it is necessary to create a system of two equilibrium equations, which will be the algebraic sums of the projections of all forces on the horizontal (x) and vertical (y) axes, which will be zero.

The original system of equilibrium equations will be:

$$\begin{aligned} \sum_{i=1}^N X_i &= -R \sin(\delta + \gamma) - F_{FR} \sin \gamma + N \cos \gamma + P \sin \gamma = 0, \\ \sum_{i=1}^N Y_i &= R \cos(\delta + \gamma) + F_{FR} \cos \gamma + N \sin \gamma - P \cos \gamma = 0, \\ F_{FR} &= kN, \end{aligned} \quad (6)$$

where X_i , Y_i – the algebraic sum of the projections of all forces acting on the top of the shoe in the projection on the x and y axes; δ – the angle characterizing the slope of the foot and covering its tops; γ – the inclination angle between the tangent to the sole of the postoperative orthopedic shoe of the plane of the support (may be in the range of $20 \div 40^\circ$, usually taken to be 25°).

Taking into account the third equation of system (6):

$$\sum_{i=1}^N X_i = -R \sin(\delta + \gamma) - kN \sin \gamma + N \cos \gamma + P \sin \gamma = 0,$$

$$\sum_{i=1}^N Y_i = R \cos(\delta + \gamma) + kN \cos \gamma + N \sin \gamma - P \cos \gamma = 0. \quad (7)$$

From the second equation of system (7):

$$kN \cos \gamma + N \sin \gamma = P \cos \gamma - R \cos(\delta + \gamma).$$

From the last equation, let's determine the value of the normal heel pressure on the surface of the shoe:

$$N = \frac{P \cos \gamma - R \cos(\delta + \gamma)}{k \cos \gamma + \sin \gamma}. \quad (8)$$

Let's transform the first equation of system (7) to the form:

$$-R \sin(\delta + \gamma) + N(\cos \gamma - k \sin \gamma) + P \sin \gamma = 0.$$

Substituting the value of the normal heel pressure on the surface of the shoe from formula (8) into the last equation:

$$-R \sin(\delta + \gamma) + \frac{P \cos \gamma - R \cos(\delta + \gamma)}{k \cos \gamma + \sin \gamma} \times$$

$$\times (\cos \gamma - k \sin \gamma) + P \sin \gamma = 0.$$

Let's reduce the last equation to a common denominator:

$$-R \sin(\delta + \gamma)k \cos \gamma - R \sin(\delta + \gamma) \sin \gamma +$$

$$+ [P \cos \gamma - R \cos(\delta + \gamma)](\cos \gamma - k \sin \gamma) +$$

$$+ P \sin \gamma k \cos \gamma + P \sin^2 \gamma = 0.$$

Let's imagine the last equation in the form:

$$R \left[\frac{\sin(\delta + \gamma)(k \cos \gamma + \sin \gamma) +}{+ \cos(\delta + \gamma)(\cos \gamma - k \sin \gamma)} \right] =$$

$$= P(\cos^2 \gamma - \cos \gamma k \sin \gamma + \sin \gamma k \cos \gamma + \sin^2 \gamma),$$

or

$$R \left[\frac{\sin(\delta + \gamma)(k \cos \gamma + \sin \gamma) +}{+ \cos(\delta + \gamma)(\cos \gamma - k \sin \gamma)} \right] =$$

$$= P(\cos^2 \gamma - k \cos \gamma \sin \gamma + k \cos \gamma + \sin \gamma).$$

From the last equation, let's determine the pressure force on the upper part of the postoperative orthopedic shoe when the sole is bent:

$$R = \frac{P(\cos^2 \gamma - k \cos \gamma \sin \gamma + k \cos \gamma + \sin \gamma)}{\left[\frac{\sin(\delta + \gamma)(k \cos \gamma + \sin \gamma) +}{+ \cos(\delta + \gamma)(\cos \gamma - k \sin \gamma)} \right]}. \quad (9)$$

The value of the normal heel pressure on the surface of the shoe, taking into account (8), will be:

$$N = \frac{P \cos \gamma}{k \cos \gamma + \sin \gamma} -$$

$$- \frac{P \cos(\delta + \gamma)(\cos^2 \gamma - k \cos \gamma \sin \gamma + k \cos \gamma + \sin \gamma)}{(k \cos \gamma + \sin \gamma) \left[\frac{\sin(\delta + \gamma)(k \cos \gamma + \sin \gamma) +}{+ \cos(\delta + \gamma)(\cos \gamma - k \sin \gamma)} \right]}.$$

Let's substitute the values from (5) into equation (9) and get:

$$R = \frac{Eba^3(\cos^2 \gamma - k \cos \gamma \sin \gamma + k \cos \gamma + \sin \gamma)}{12\rho L \left[\frac{\sin(\delta + \gamma)(k \cos \gamma + \sin \gamma) +}{+ \cos(\delta + \gamma)(\cos \gamma - k \sin \gamma)} \right]}. \quad (10)$$

According to the results of the computational experiment, graphic dependences of the change in the force of pressure on the upper part of the postoperative orthopedic shoe will be built when the base is bent, as a function of the inclination angle between the tangents to the sole of the foot of the support plane.

6. Research results

The calculation results are shown in Fig. 4, 5. The data obtained for the thickness of the sole 1 and 2 cm.

Graphic analysis in Fig. 4, 5 shows that the greatest value of the pressure force on the upper part of the postoperative orthopedic shoe when bending the sole is observed at an angle $\gamma = 25^\circ$. With an increase, a decrease in this force is observed. This is due to a change in the orientation of the vectors of all forces.

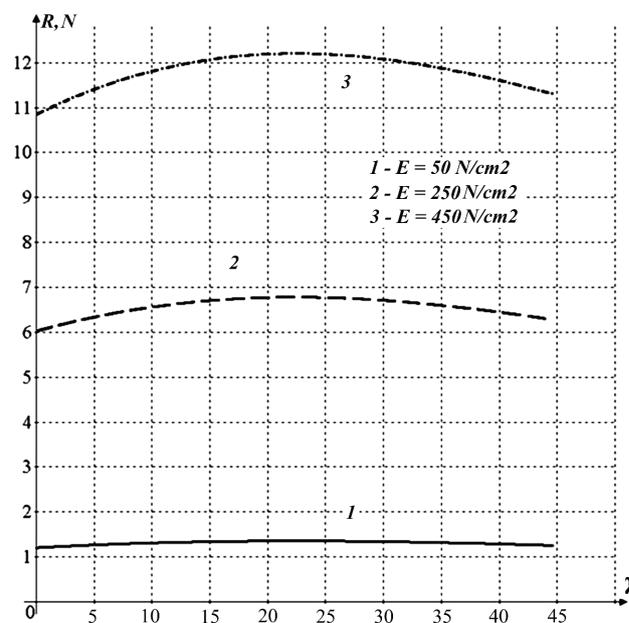


Fig. 4. Dependencies $R=f(\gamma)$ at $a=1$ cm

The tension across the supporting belts with Velcro fasteners can be determined by the following formula:

$$T = \frac{R}{2 \sin \alpha}, \quad (11)$$

where T – tension of the supporting belts with Velcro fasteners; α – inclination angle of the supporting belts to the plane perpendicular to the vector of pressure force on the upper part of the postoperative orthopedic shoe (its value can vary within $10\div 20^\circ$ depending on the design of the top of the shoe).

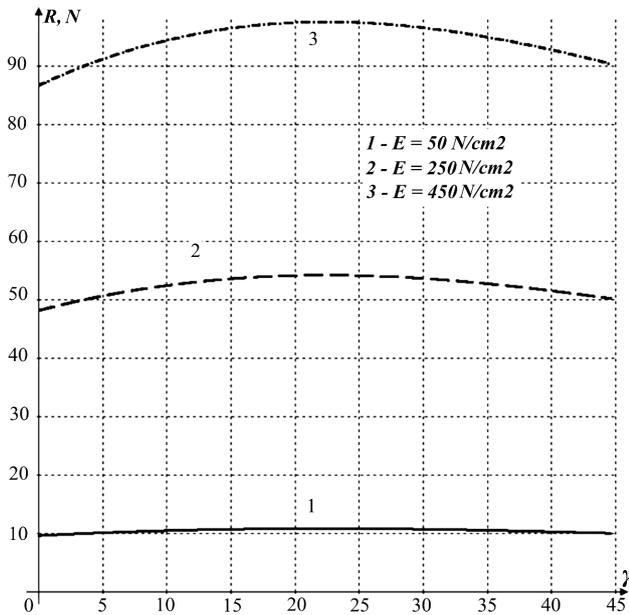


Fig. 5. Dependencies $R=f(\gamma)$ at $a=2$ cm

The practice of operating the «Velcro» fastener shows that with an increase in the tension of the supporting tape (with loops), the detachment force at the beginning increases to a certain maximum, and further, with an increase in tension, the detachment force decreases to almost zero. This circumstance may affect the reduction of reliability of the joints of the tops of orthopedic shoes. Therefore, it is important to conduct a series of experimental studies to study the influence of structural and operational factors on the value of the detachment force [12].

The coefficients in the regression equation for the rotatable plan are determined by the following formulas:

$$\begin{aligned}
 b_0 &= a_1 \sum_{j=1}^N y_j - a_2 \sum_{i=1}^k \sum_{j=1}^N x_{ij}^2 y_j, \\
 b_i &= a_3 \sum_{j=1}^N x_{ij} y_j, \\
 b_{ij} &= a_4 \sum_{j=1}^N x_{ij} x_{ij} y_j, \\
 b_{ii} &= a_4 \sum_{j=1}^N x_{ij}^2 y_j + a_6 \sum_{i=1}^k \sum_{j=1}^N x_{ij}^2 y_j - a_7 \sum_{j=1}^N y_j,
 \end{aligned}
 \tag{12}$$

where $a_1...a_7$ – constant coefficients.

The value of the sum to determine the coefficient b_0 is determined by the formula:

$$\begin{aligned}
 \sum_{j=1}^N y_j &= 23.0 + 19.5 + 16.0 + 14.5 + 15.0 + 18.0 + 17.0 + \\
 &+ 28.0 + 25.0 + 24.8 + 25.2 + 25.3 + 24.8 = 276.1.
 \end{aligned}
 \tag{13}$$

The value of the sum to determine the coefficient b_{ij} is determined by the formula:

$$\sum_{j=1}^N x_{ij} x_{ij} y_j = 23.0 - 19.5 - 16.0 + 14.5 = 2.0.
 \tag{14}$$

The value of the sum to determine the coefficient b_i is determined by the formula:

$$\begin{aligned}
 \sum_{j=1}^N x_{1j} y_j &= 23.0 - 19.5 + 16.0 - 14.5 - \\
 &- 1.414 \cdot 15.0 + 1.414 \cdot 18.0 = 9.24, \\
 \sum_{j=1}^N x_{2j} y_j &= 23.0 + 19.5 - 16.0 - 14.5 - \\
 &- 1.414 \cdot 17.0 + 1.414 \cdot 28.0 = 27.55.
 \end{aligned}
 \tag{14}$$

The value of the sum to determine the coefficient b_{ii} is determined by the formula:

$$\begin{aligned}
 \sum_{j=1}^N x_{1j}^2 y_j &= 23.0 + 19.5 + 16.0 + 14.5 + \\
 &+ 1.414^2 \cdot 15.0 + 1.414^2 \cdot 18.0 = 138.98, \\
 \sum_{j=1}^N x_{2j}^2 y_j &= 23.0 + 19.5 + 16.0 + 14.5 + \\
 &+ 1.414^2 \cdot 17.0 + 1.414^2 \cdot 28.0 = 162.97.
 \end{aligned}
 \tag{15}$$

The value of the sum is determined by the formula:

$$\sum_{i=1}^k \sum_{j=1}^N x_{ij}^2 y_j = 138.98 + 162.97 = 301.95.
 \tag{16}$$

Then, taking into account the significance of the coefficients in the regression equation, taking into account equations (11), let's obtain the dependence of detachment force P_D of the Velcro tape on the tension force P_T and the tape width h in the named values.

In the named values, the dependence of the force of detaching the «Velcro» tape P_D from the tension force P_T , and the tape width h for the variant for the density of the location of the hooks 60 hooks on 1 cm² has the form:

$$\begin{aligned}
 P_D &= 0.944 \cdot P_T - 0.047 \cdot P_T^2 - 0.004 \cdot h^2 + \\
 &+ 0.326 \cdot h + 1.924.
 \end{aligned}
 \tag{17}$$

Fig. 6 is the graphical dependence of the force of detaching a Velcro film P_D on the tension force, P_T and the tape width h .

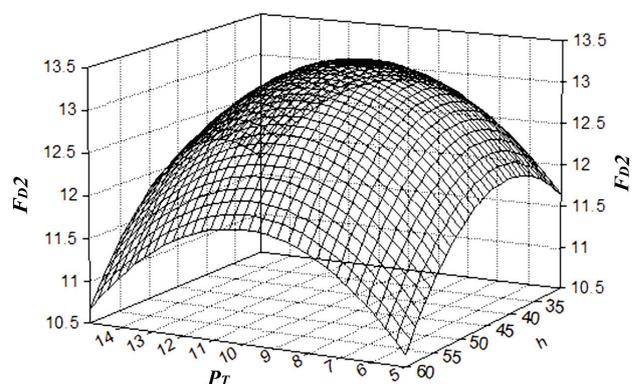


Fig. 6. Response surface function for F_D

The detachment force grows with increasing width and reaches a certain maximum. A further increase in width leads to a decrease in the magnitude of the detachment force. This can be explained by a decrease in the distributed pressure in the contact zone.

7. SWOT analysis of research results

Strengths. On the basis of the obtained values of the tension of the supporting belts with the Velcro fasteners, it is possible to determine their number and design – the width and density of the location of the hooks per unit plane. To ensure the fastening of fasteners, it is necessary to choose the correct type of fastener, the width and length of the active area of the contact, the density of the hooks. To test the correctness of the made assumption, in theoretical studies, a series of experimental studies using active experiment planning is implemented. As a result, the resulting regression, by definition, the effect of tape tension with loops and its width on the magnitude of the force of detaching the «Velcro» fastener. With the right selection of parameters for parts for keeping shoes on the foot, the time spent on the selection and purchase of quality materials for its manufacture will decrease.

Weaknesses. The weaknesses of the study include the following:

– the force of detachment with increasing tension first increases and reaches a certain maximum. Further growth leads to a decrease in the magnitude of the detachment force. This may be due to a violation of the conditions of interaction between the loops and hooks. For example, increasing the distance between the hooks;

– with an increase in the width of the tape with loops, a similar pattern is observed. The detachment force grows with increasing width and reaches a certain maximum. A further increase in width leads to a decrease in the magnitude of the detachment force. This can be explained by a decrease in the distributed pressure in the contact zone.

These circumstances must be considered when designing the design of orthopedic and postoperative footwear.

Preliminary calculations have shown a great deal of labor in calculating the results of experimental studies and building regression equations.

Opportunities. To automate the process of designing orthopedic and postoperative shoes, it is necessary to develop a program that allows to perform calculations of the corresponding forces and tension across the supporting belts, depending on the design and types of material of individual elements. And also get the regression equation to determine the effect of tape tension with loops and its width on the magnitude of the detachment force of the «Velcro» fastener.

Threats. To implement the research results, the company will need initial investments, since the production of products is labor-intensive and material-intensive.

The negative impact on the object of research is the design parameters of orthopedic postoperative footwear, based on complex theoretical and experimental studies. This increases the time spent on its production for use by people who need orthopedic postoperative footwear.

8. Conclusions

1. Determined:
 - distribution load on the sole, equal to 50–450 N;
 - pressure force on the upper part $R=10$ N;
 - friction coefficient of the foot with the material $k=0.2$;
 - inertia moment of the sole section $I_x=0.66$.
2. The analysis of graphic dependences of the value of the pressure force on the upper part of the postoperative orthopedic shoe when bending the sole at an angle $\gamma=25^\circ$. When $\rho=2$ cm, $a=2$ cm, $b=8$ cm, $L=16.75$ cm, $\delta=25^\circ$.
3. The forces of detaching the tape with loops with increasing tension of the supporting tape and increasing its quantity are determined, which are equal to 5 N. Based on the obtained values, it is possible to determine the number of supporting belts of half-pairs of shoes with Velcro fasteners, which will be equal to 4. And also their designs are 60 mm wide and the density of hooks per unit plane is 60 hooks on 1 cm².

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