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Information model for the evaluation of the efficiency of osteoplasty performing in case of amputations on below knee

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ABSTRACT

Based on the information model different variants of osteoplasty, taking into account the persistence, value of critical loading and flexibility of amputation stump below are substantiated. The studies of strength assessment and values of critical load on the stump below knee showed that osteoplastic amputations have obvious advantages as compare d with myoplastic amputations. From the point of view of critical load rather long stumps are inferior to stumps in middle and upper thirds. The character of malleolus bones connection influences the conditions of stump functioning. The most rational are the connections conceptually similar with rigid bony bridge.

Keywords: information model, amputation, myoplasty, osteoplasty, synostosis, strength, flexibility, critical load

1. INTRODUCTION

General progress and mechanization stipulate the increase of traumas and vascular diseases leading to the amputation of the extremities. As a rule the amputation of extremities is accompanied with partial or complete disability[1]. At the same time, disabled persons population with amputation stumps, especially those who was operated as a result of traumas, is perspective in terms of the recovery of the lost function of the extremity by means of prosthesis. In spite of the fact that nowadays considerable progress is achieved in the sphere of prosthetics of the disabled persons regarding conventional and bioelectric prostheses, the problem of the extremity amputation and rehabilitation of this group of disabled persons can not be considered to have been solved. Various diseases and faults of amputation stump are developed in greater part of the patients[1,2,3], observed in 60-85% of the patients. The task of creating new working organ – the stump, turned out to be very complex[4]. During centuries the best surgeons developed and promoted various methods of operations – from simple limb truncation to complex plastic operations (osteoplasty , fascioplasty, myoplasty). At the same time, nowadays there are supporters and detractors or this or that method, showing that this problem has not been studied sufficiently. Particularly insufficiently and contradictorily the problems of the role and place of osteoplasty in case of amputation are considered in literature.

If the application of such plastic operations in epimetaphyseal zone as Pirogov amputation, Gritti-Shimanovskiy amputation[5,6] are mainly known, then the great contradictions emerge while assessing Bier's diaphyseal osteoplastic amputations. One group of authors considers these operations as expedient and useful [7,5,8], others[6,9] are reservedly disposed towards such operations. In our opinion, such divergent assessments appear as a result of insufficient study of the problem, lack of scientific substantiation of such operations, taking into account mathematical modeling[10,4] of different variants of osteoplasty and assessment of the persistence and biomechanical conditions of the prosthetics[11] from the point of view of the mechanics of deformable solid body as it is known that the absence of pain and persistence that provides ambulation stability, are the most important aspects in prosthetics.

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2. AIM OF THE RESEARCH

Substantiate different variants of osteoplasty, taking into account the resistance, value of critical loading and flexibility of amputation stump below knee by means of information model.

3. OBJECT AND METHODS OF STUDY

When evaluating the stability the bone can be considered as a rectilinear rod, its cross-section is small as compared with the length and it is pressed with a small force[12]. We will assume, that the force of compression is directed along the axis of the bone and is applied in the center of gravity of the cross-section. If the force of compression is small, then the bone will experience the curtailing. Gradually increasing the force the state can be reached when the violation of initial form elastic equilibrium occurs and minor bending of the rod axis takes place (Figure 1).

Force P_{kp}, at which two forms of elastic balance are possible – rectilinear and curvilinear – is called critical and the state of the system, correspondingly – loss of stability. The value P_{kp} is determined while stability calculation in the same way as the value of destructive force while strength calculation, however, the value of critical force, depending or the length of the bone, can be several times less than the value of the destructive force. It should be noted that the axis of the bone is not a direct line, that is why, the bending moment $M_Z \neq 0$ at small values of loading P. If the value of the force P is greater than the value of critical force P_{kp} it is equivalent to bone destruction, because the non-stable form, of the balance will be inevitably lost, that is connected with practically unlimited growth of deformations and stresses.

Particular danger of destruction as a result of stability loss is that as a rule it occurs unexpectedly at low values of strains when the stress of the bone is not exhausted. Thus, to calculate the compressed bone on the persistence, it is necessary to master the ways of determining the values of critical loadings P_{kp}. Among different calculations of elastic systems strength we will apply Eulerian approach[13]. In this case the elastic balance of the bone will be considered as the balance of the rod, compressed by the central force P_{kp}. Let us consider the conditions when the balance of the rod with the convex axis is possible.

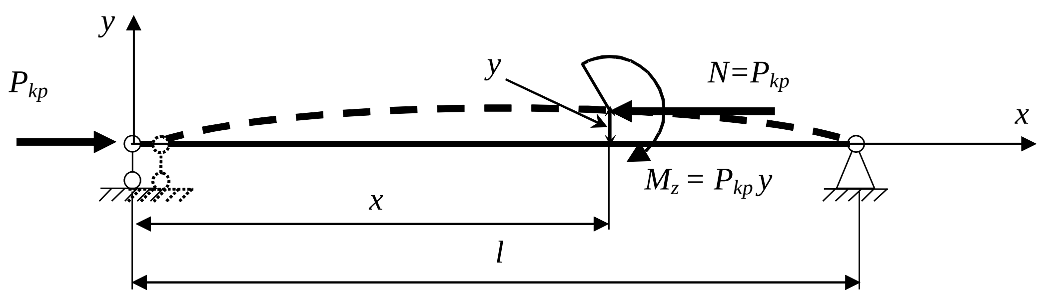

Figure 1. Calculation scheme

In transactions the stresses will occur both from longitudinal force $N=P$ and from deflection moment $M_Z = -P_{kp} \cdot y$.

The coordinates of elastic line points will be denoted by y, x. In case of small deflections the differential equation of the elastic line can be applied

$$E I_z y'' = M_z. \tag{1}$$

Bend of the rod in the given case occurs in the plane of figure, that is why, in (1) axial moment of the cross-section of inertia relatively the axis z and bending moment M_z relatively the same axis is taken, it equals

$$M_z = -P_{kp} y. \tag{2}$$

Thus, from (1) and (2) we obtain

$$E I_z y'' = -P_{kp} y. \tag{3}$$

For tibia bone the moment of inertia I_z depends on x, because the cross-section of the bone changes along its length. That is why, differential equation (3) in quadratures is not solved. Determination of v the absolute value of the force P_{kp} when elastic balance is possible is shown in Figure 1, where it is necessary to compare the stability of the stump of the lower part of the leg, depending on the type of the osseous synostosis.

That is why, we will assume that $E\ I_z = const$ then for critical force value we have the known formula of L. Euler, that is obtained as a result of differential equation solution (3)

$$P_{kr} = \frac{\pi^2 EI}{l^2}, \tag{4}$$

where E – is Young's modulus, l – is the length between fixations

The impact of fixation conditions on the value of critical force is taken into account by means of the coefficient of the given length μ. Then the value of critical force is determined by the formula

$$P_{kr} = \frac{\pi^2 EI}{(\mu\, l)^2}. \tag{5}$$

It should be noted that the formulas (4), (5) can be used when the real values of bone elasticity

$$\lambda = \frac{\mu \cdot l}{\sqrt{I/A}}$$

are greater than the critical values, determined on the base of its physical mechanical properties.

$$\lambda_u = \sqrt{\frac{\pi^2 E}{\sigma_{pr}}} \tag{6}$$

where σ_{pr} – is proportionality boundary of the bone's material as such parameter is not given in literature, then instead of its value the strength boundary value $\sigma_{pr} \approx \sigma_{\max}$ can be taken[6], because the bone is the material with the expressed brittle properties.

4. RESULTS OF THE RESEARCH AND DISCUSSION

For the sake of comparison we determine the value of P_{kp} for two cases: 1) bones function independently; 2) bones are connected. Let us assume, that on the top the drive joint (knee joint) is located, and below – spherical joint (the support of the prosthesis). Calculation schemes for these cases are given in Figure 2 and Figure 4.

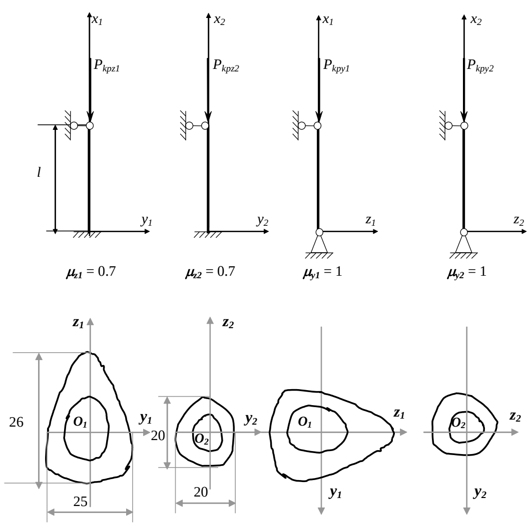

Figure 2. Calculation scheme for the case when the bones work in compression independently

First case. Bones function independently. We do not take into consideration the interaction with muscles, because the muscles increase the value of critical force, i.e., facilitates the bone work in compression.

Moment of inertia of the cross-sections of large tibia bone and small fibula bone relatively main central axis z and y were determined numerically, in COMPAS program environment.

$$I_{z1}=\int_{A_1} y^2 dA = 13450\ мм^4,$$
$$I_{y1}=\int_{A_1} z^2 dA = 34160\ мм^4, \tag{7}$$
$$I_{z2}=\int_{A_2} y^2 dA = 4610\ мм^4,$$
$$I_{y2}=\int_{A_2} z^2 dA = 4815\ мм^4.$$

For determination of the moments of inertia of the bones cross-sections by the formulas (7) it is necessary to have the cross-section itself or obtain its dimensions and the geometry by means of corresponding measurements on the given bone areas of the cross-sections of large tibia bone A_1 and small fibula bone A_2 equal

$$A_1 = 286\ \text{mm}^2,\ A_2 = 194\ \text{mm}^2.$$

Elasticity of large tibia bone (1) and small fibula bone (2) in the plane $x_i o_i z_i$(sagittal) and in the plane $x_i o_i y_i$ (frontal) for the length $l = 400\ mm$.

$$\lambda_{z1} = 40{,}3;\ \lambda_{y1} = 36{,}6;\ \lambda_{z2} = 57{,}4;\ \lambda_{y2} = 80{,}3.$$

As $\lambda_i \geq \lambda_u = 30{,}8$ then the values of critical forces P_{kpzi} and P_{kpyi} were calculated by the formulas (4), (5)

$$P_{kpzi} = \frac{\pi^2 EI_{zi}}{(\mu_{zi} l)^2},\ P_{kpyi} = \frac{\pi^2 EI_{yi}}{l^2},\ i = 1,2. \tag{8}$$

For large tibia bone

$$P_{kpz1} = 22{,}4\ kH, \qquad P_{kpy1} = 27{,}8\ kH.$$

For small fibula bone

$$P_{kpz2} = 7{,}7\ kH, \qquad P_{kpy2} = 3{,}9\ kH.$$

If we determine the value of critical forces for large tibia bone of $l=400mm$, when this bone is in normal state, i.e., axial joint functions above and below (the length μ_{z1} = 0,5), then the forces P_{kpy1} will coincide and the value of the force P_{krz}^{norm} = 48,3 kH, than is it will be almost two times greater than critical loading for the stump P_{kpz1}= 22,4 kH. This is stipulated by the fact that in normal state axis of the cross-section z (Figure 2) is perpendicular to the axes of the joints – to show more obviously the impact of the stump's length or the value of critical force in Figure 3, the graphs of the dependence of critical force in sagittal P_{kpz1} and frontal P_{kpy1} planes on the length of large tibia bone. The values of critical forces for the most spread length of the stump – 180mm:

$$P_{kpz1} = 110\ kH, \quad P_{kpy1} = 137\ kH, \quad P_{kpz2} = 37{,}8\ kH, \quad P_{kpy2} = 19{,}4\ kH.$$

Consequently, shortening of the stump 2.22 times leads to the increase of maximum loads $2.22^2 = 4.94$ times.

The second case. Bones are connected by means of bony bridge (synostosis). In this case the bones are rigidly bound. That is why, for determination of critical forces and flexibility of such system it is necessary to determine the moments of inertia relatively main central axes, passing across the common centre of weight of the sections of both bones, as the axis z coincides with axes z_1, z_2 (Figure 4) and is the axis of symmetry of the system, then the centre of weight is on this axis and its location is determined by the formula.

$$z_c = \frac{A_1 z_1 + A_2 z_2}{A_1 + A_2} = \frac{286 \cdot 43 + 194 \cdot 9}{286 + 194} = 29,26\ mm$$

where $z_1 = 9 + 34 = 43\ mm$, $z_2 = 9\ mm$.

We assume that the distance between the bones equals 34 mm. Moments of inertia of the joint bones relatively main central axes of the inertia

$$Iz = Iz_1 + Iz_2 = 13450 + 4610 = 18060\ mm^4$$

$$Iy = Iy_1 + a_1^2 A_1 + a_2^2 A_2 + Iy_2 = 34160 + 13,74^2 \cdot 286 + 4815 + 20,26^2 \cdot 194 = 172600\ mm^4$$

where a_1, a_2 – distances between the axes y_1 and y_2 and y correspondingly

$$\grave{a}_1 = z_1 - z_c = 43 - 29.26 = 13,74\ mm,$$
$$\grave{a}_2 = z_{\tilde{n}} - z_2 = 29.26 - 9 = 20,26\ mm.$$

We find the critical forces of the system of two bones in the planes xCz (sagittal) xCy (frontal) on conditions that they are connected (Figure 4)

$$P_{kpz} = \frac{\pi^2 EI_{zi}}{(\mu_{zi} l)^2} = \frac{3.14^2 \cdot 13,2 \cdot 18060}{(0,7 \cdot 400)^2} = 30\ \hat{e}H \qquad (9)$$

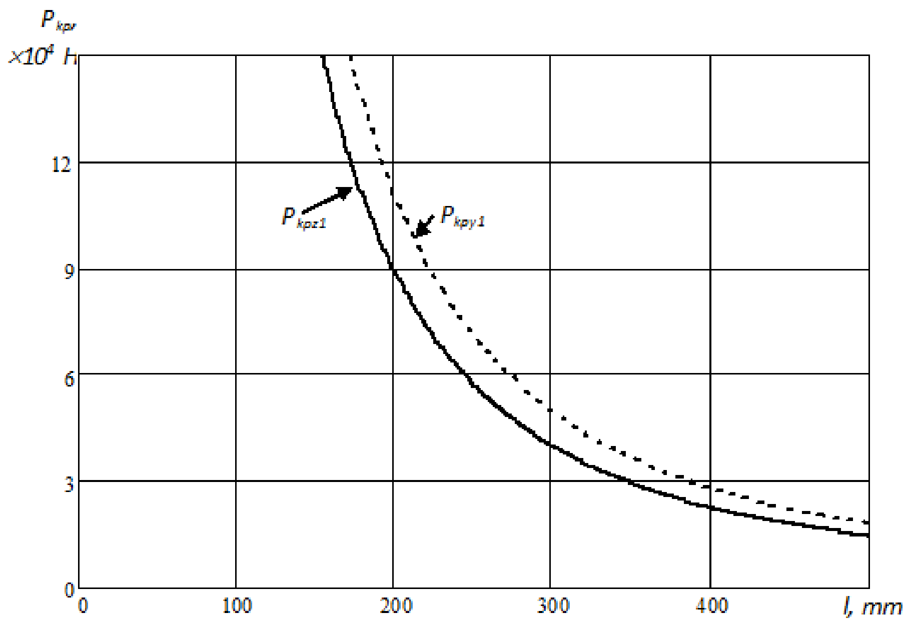

Figure 3. Dependence of the value of critical force on the length of the stump in two planes

$$P_{kpy} = \frac{\pi^2 EI_y}{l^2} = \frac{3.14^2 \cdot 13,2 \cdot 172600}{400^2} = 287\ \hat{e}H \qquad (10)$$

Thus, in case of osteoplasty on sagittal plane xCz, characteristics of the rigidity do not practically change as compared with muscular plasty. Critical force remains without changes.

$P_{kpz} \approx P_{kpz1} + P_{kpz2}$ and flexibility λ_{z1}=40,3, λ_{z2}=57,4,λ_z=45,67 have close values.

In frontal plane $x\ c\ y$ the system of the connected bones is more stable.

$$\frac{P_{kp}}{P_{kpy1} + P_{kpy2}} = 4.44,$$

i.e., critical load on the whole increases 4.44 times.

Generally at bones synostosis the rigidity of the obtained system is considerably higher than that of the system, when the bones work independently, i.e. in case of myoplastic amputation.

If bones are joint by the scheme 1 (Figure 5), several vases are possible.

In case of the Figure 5a, if the adjustment of the prosthesis is pour, in AB cross-section the bending moment will emerge.

$$M_{AБ} \approx P_2 \bullet a \quad (10)$$

Even in case of proper adjustment of the prosthesis it is practically impossible to provide the uniform distribution of frictional forces on the contact surface AA_1, because the forces P_1 and P_2 in general case are not equal. That is why, it is necessary to provide such construction of the prosthesis that would compensate this irregularity.

If the bones are connected according to the scheme in Figure 5b and Figure 5c, the effects considered above, will occur, because it is practically impossible to perform the connection of the bones, when the uniform load distribution could be provider without misalignment. However, in this case such effects are poorly resolved.

Connection schemes, given in Figure 5c and Figure 5d are not desirable because under the impact of vertical loading P_2 the bending moment $M_A \approx P_2 \bullet a$ will appear in the cross-section A.

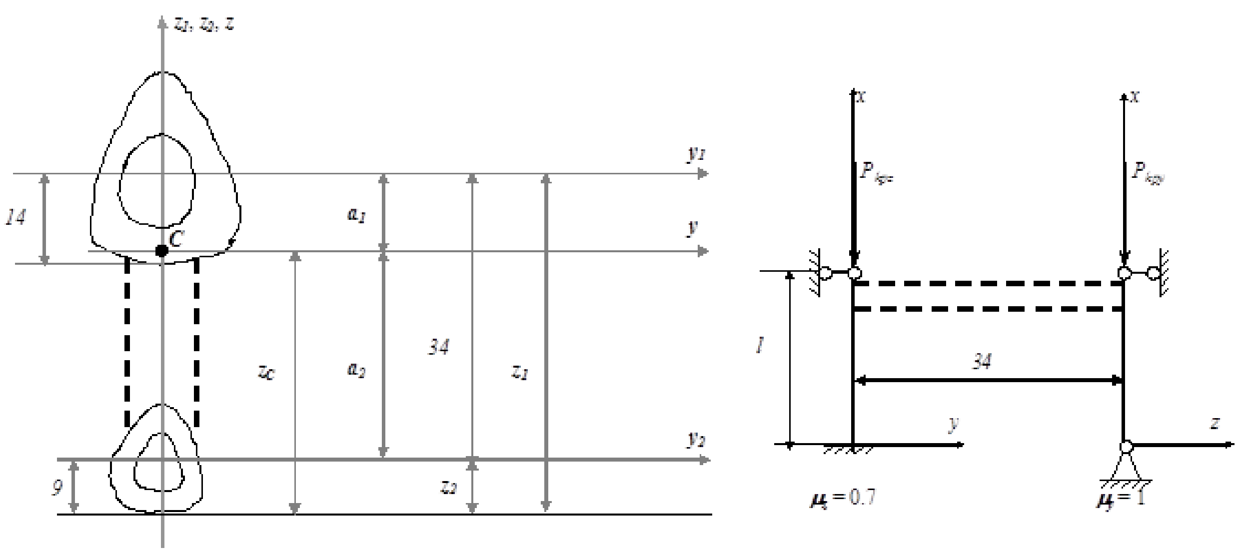

Figure 4. Calculation scheme for the case when the bones are connected

Such connections are acceptable, if the distance a is very small, the force P_1 is not directed vertically and the angle between longitudinal axis of the bone and the direction P_2 is close to zero.

From the point of view of the stability provision of the system, consisting of two bones the better are rigid joints, considered above (Figure 5b)

Under normal loads the problem of the strength of the "bones" of the leg after amputation does not exist. The possibility of losing the equilibrium that coned lead to the destruction is not actual. However, under ant load the bone is deformed and this deformation is mainly typical, in this case. Both the compression deformation and buckling strain (Figure 1) take place.

Transverse deformation of longitudinal bending takes place at any, even minor load. This is stipulated by the fact that longitudinal axis of the bone is not straight, i.e., centers of the weight of the cross-sections are not located on the same vertical line. Under such conditions of bone work because when the load on the bone attains critical values it's deformation increases practically infinitely. That is why we continue studying the stability of bones in conditions, close to real conditions. It should be noted that the probability that under ordinary loads the bone will lose the stability and the destruction or bone fracture will take place, is rather small. However, when loads approach critical values large bending deformations, that will cause pain or, at least, discomfort for the patient, will appear in the bone.

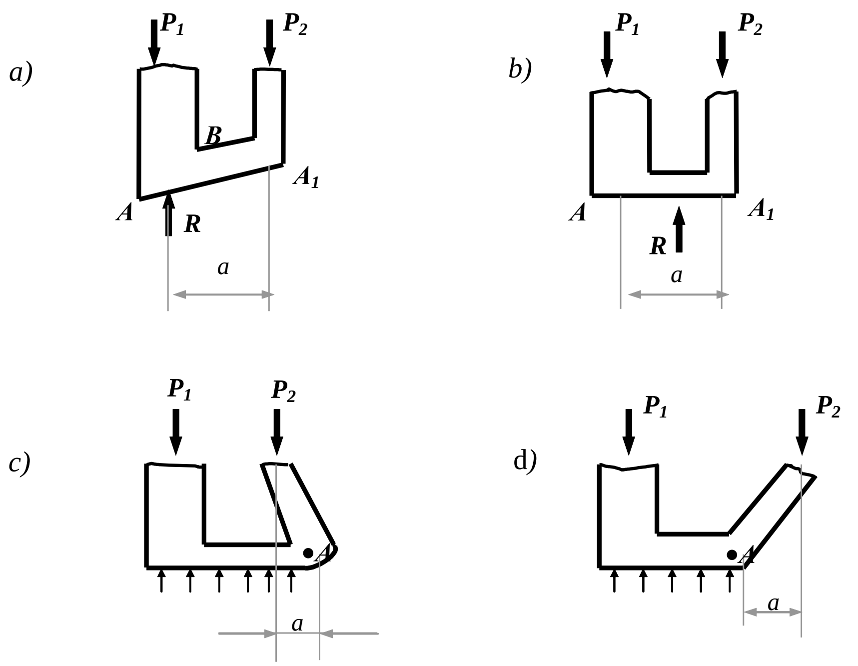

Figure 5. (a, b, c, d) schemes of possible variants of osteoplasty at amputation stump below knee

Also it should be noted that under dynamic loads the danger of losing the strength considerably grows. That is why, in the process of the stump formation it is necessary to create such conditions that after amputation admissible critical loads were maximum. The less real loads on the bone are as compared with critical ones, the less are bone deformations, the better it performs its functions and general state of the patient improves.

5. CONCLUSIONS

The studies of strength assessment and values of critical load on the stump of the malleolus showed that osteoplastic amputations have obvious advantages as compared with myoplastic amputations. They assume dangerous loads, that exceed loads in case of myoplastic amputations 2.5-4.5 times. From the point of view of critical load rather long stumps are inferior to stumps in middle and upper thirds. The character of malleolus bones connection influences the conditions of stump functioning.

Bones connection shifts are not desirable as they will complicate the process of prosthetics. The most rational are the connections conceptually similar to rigid bony bridge.

REFERENCE

[1] Preißler, S., Thielemann, D., Dietrich, C., Hofmann, G. O. and et al., "Preliminary Evidence for Training-Induced Changes of Morphology and Phantom Limb Pain," Front Hum Neurosci, 11, 319 (2017).

[2] Hsu, E. and Cohen, S. P., "Postamputation pain: epidemiology, mechanisms, and treatment," Journal of Pain Research 6, 121-136 (2013).

[3] Kadurin, O. K., Vyrva, O. I. and Leontieva, F. S., "Biofizychni vlastyvosti kompaktnoi kistkovoi tkanyny," Naukove vydannia Prapor, Kharkiv, (2007).

[4] Zlepko, S. M., Tymchyk, S. V., Novikova, A. O., Moskovko, M. V., Zlepko, A. S., Omiotek, Z. and Małecka-Massalska, T., "An informational model of sportsman’s competitive activities," Proc. SPIE 10031, (2016).

[5] Kahle, J. T., Highsmith, M. J., Kenney, J., Ruth, T. and et al., "The effectiveness of the bone bridge transtibial amputation technique: A systematic review of high-quality evidence," Prosthetics and Orthotics International 41(3), 219-226 (2017).

[6] Nijmeijer, R., Voesten, H. G. J. M., Geertzen, J. H. B., Dijkstra, P. U., "Disarticulation of the knee: Analysis of an extended database on survival, wound healing, and ambulation," Journal of Vascular Surgery 66(3), 866-874 (2017).

[7] Bosse, M. J., Morshed, S., Reider, L., Ertl, W., and et al., "METRC. Transtibial Amputation Outcomes Study (TAOS): Comparing Transtibial Amputation With and Without a Tibiofibular Synostosis (Ertl)," Procedure. J Orthop Trauma 31(1), 63-69 (2017).

[8] Shevchuk, V. I., Bezsmertnyi, Y. O. and Kyrychenko, V. I., "Muscular plastic during amputation and abdominal shaft," Ortopedija travmatologija i protezirovanie 4, 13-18 (2010).

[9] Shevchuk, V. I., Bezsmertnyi, Y. O. and Maiko, V. M. "Kistkova plastyka pry amputatsiiakh ta reamputatsiiakh nyzhnikh kintsivok," Ortopedija travmatologija i protezirovanie 1, 47-55 (2011).

[10] Tosun, B., Selek, O., Gok, U. and Tosun, O., "Medial gastrocnemius muscle flap for the reconstruction of unhealed amputation stumps," Journal of Wound Care 26(8), 504-507 (2017).

[11] Gozhyi A. and Kalinina I., "Information system for a fuzzy cognitive analysis and modeling," Informatics Control Measurement in Economy and Environment Protection 4 (2), 31-33 (2014).

[12] Ryniewicz, W. and Ryniewicz, A., "Model analysis of the stomatognathic system restorations using prosthetic bridges," Przegląd Elektrotechniczny 5, 17-20 (2015).

[13] Hotra, O., Boyko, O. and Zyska, T., "Improvement of the operation rate of medical temperature measuring devices," 13th International Scientific Conference on Optical Sensors and Electronic Sensors 9291, (2014).