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SOLUTIONS TO IMPROVE MOBILITY OF THE PLASTER WALKING BOOT IN PATIENTS WITH PATHOLOGIES OF THE LOWER LIMB

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Abstract: *In this paper, two technical solutions are proposed to improve the mobility of the plaster walking boot in the case of patients with pathologies of the lower limb. Having as reference element the concepts of biomimicry and bionics, an analysis of the principle of locomotion in the animal kingdom (kangaroo) is made. Based on an extensive bibliographic study, the distribution of the load distributed in the contact area between the plastered boot and the bionic displacement system is defined. Using the finite element method, the two proposed bionic systems are modeled in order to determine the laws that govern the distribution of efforts (forces and moments). Knowing the laws of variation and the size of the efforts, the elements that make up these bionic displacement systems can be optimally dimensioned (from the condition of strength, rigidity, stability and / or economy).*

Key words: *Biomimicry, Lower Limb, Efforts, Bionic Displacement Systems*

1. INTRODUCTION

To solve various pathologies of the lower limbs (injuries or fractures) you can use a series of surgical or orthopedic methods. Surgical treatments involve a partial or total immobilization of the affected area (for example, the use of plaster boots for the modeling of which calcium sulphate semi-hydrate - CaSO4 (H2O) ½ is used, according to Figure 1.a) [1]. The structure of the plaster walking boot also includes a posterior plaster splint that ensures high rigidity during locomotion, relatively low mass but does not allow easy movement of the patient, this situation leading to a difficulty in maintaining the tone of the muscles of the immobilized segment. Even if a walking frame is added to this system (with a height varying between 1 and 2 cm), made of plastic or rubber, the difficulty of locomotion persists. In addition, during locomotion, because the possibility of movement of the ankle joint (pivotal synovial joint - according to Fig. 1.b) and of the foot joints (sliding joints - according to Fig. 1.c) is reduced, an external rotational movement is generated at the knee joint (pivotal joint). This type of movement can, under certain conditions, cause various pathologies in the knee joint.

Orthopedic treatment involves the reduction and semi-rigid immobilization of the affected area.

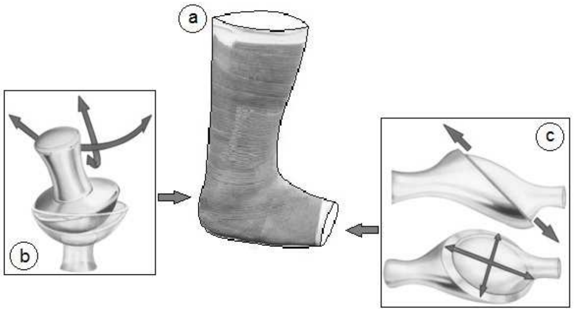

Fig. 1. a – plaster walking boot; b - pivotal joint; c - sliding joint.

To avoid such a situation, this study proposes a series of mechanical systems that can be attached to the plaster cast femur-foot so that the patient's movement is easy and correctly anatomical. The design of such a system can have as a starting point biomimicry or bionics. The term biomimicry was coined by Otto

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Schmitt in 1957 and in 1960 Jack E. Steele defined the term bionics as the science of systems that have certain functions copied from nature or that represent the characteristics of natural systems or their analogues [2-6].

The locomotion systems studied in this paper can be used both for people with various pathologies of the lower limbs (in order to improve their locomotion) but also for people without pathologies of the lower limbs (various recreational activities) using the same fastening system.

2. MATERIALS AND METHODS

The main source of inspiration (Fig. 2), for a first proposed bionic system (Fig. 3) - generically called SB1, is the kangaroo locomotion system.

Analyzing the musculoskeletal structure of the kangaroo's hind legs, it can be seen that the muscles are particularly strong and the tendons extremely long. They register large changes in length like an elastic element which by elongation stores potential deformation energy, Ud.

$$L_e = \frac{G \cdot \Delta l}{2} \qquad (1)$$

$$L_i = \frac{N^2 \cdot l_o}{2 \cdot E \cdot A_o} = U_d \qquad (2)$$

where: Le represents the external mechanical work produced by the gravitational force G acting on the tendon, Li is the internal mechanical work produced by the axial force N (generated by the gravitational force G), E represents the longitudinal modulus of elasticity (Young's modulus) of the tissue of the tendon [7], Ao is the cross-sectional area of the tendon.

According to the principle of energy conservation, the external mechanical work is equal to the internal mechanical work or the potential deformation energy [8]. The potential deformation energy is released when the kangaroo pushes up and the tendon contracts again. Some studies estimate that in the animal kingdom, tendons can store up to ten times more elastic energy than muscles [9 - 15].

Thus, the femur - foot plaster apparatus is positioned on the structure of bars, rigidly connected, expressed by means of nodes 1 - 11 - 2 - 9 - 3 - 14 - 4 - 5 from Fig. 3. The numbering of the nodes is completely random, their highlighting allowing the identification in the work of different areas of the bionic displacement system but also can represent areas of rigid connection of bars or flat joints (depending on the particularities of the bionic displacement systems studied).

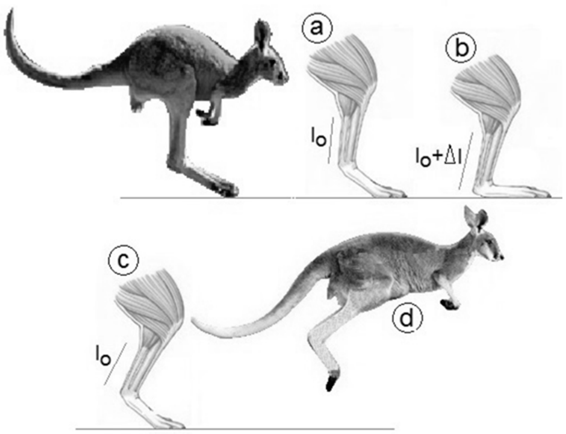

Fig. 2. The fundamental principle of kangaroo locomotion.

a - the contact with the ground takes place and the tendon has the length lo; b - the tendon lengthens accumulating potential deformation energy (elastic energy); c - the tendon returns to its initial length releasing the stored elastic energy; d - by releasing the elastic energy the kangaroo moves.

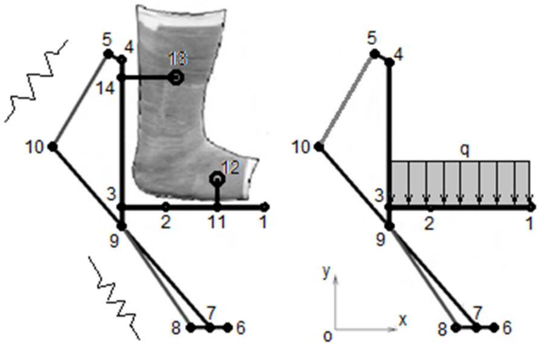

Fig. 3. Bionic displacement system, SB1.

In the contact area between the plaster cast femur - foot and bars 1 - 2 - 3, a distributed load is generated, governed by different laws of variation depending on sex, age, way of loading the human body, etc. [16 - 32]. In nodes 7 and 9 the bars 6-8, 7-10 are connected by means of movable flat joints.

Because the femoral - foot plaster apparatus has a high rigidity, it is considered that, in this application, the distributed load q is a uniformly distributed one. Thus, the length of segment 1 - 3 is considered to have the value of 300 mm and the applied mass of 70 kg thus resulting in a uniformly distributed load q = 2.289 N/mm. Segments 8-9 and 5-10 are elastic elements whose behavior can be quantified, in the most general case, by means of the relation:

$$G = k \cdot \Delta l \qquad (3)$$

where: k represents the constant of the elastic element and Δl is the elongation of the elastic element as a function of the weight force G applied to the structure SB1.

Table 1 defines the lengths of the segments that form the bionic displacement system, SB1. The dimensions defined in Table 1 are reported for a male person with a height of 1.78 meters and a mass of 70 kilograms.

Table 1

Linear characteristics of the bionic displacement system, SB1.

SB1	segment	1-3	3 - 9	3 - 4	4 - 5	9 - 10	9 - 7	7 - 6	7 - 8
	length, mm	300	39.5	314.6	33.4	224.9	286.3	36.5	39.5

The dimensioning of the constructive parts of the SB1 model can be achieved by means of the finite element method. In this case, the RDM 6.19 program is used. In plane modeling of the structure of the SB1 bionic system, according to Fig. 4, allows to establish the magnitude of the stresses (N - normal force, T - shear force, Mi - bending moment) of each component element depending on the intensity of application of the uniformly distributed load elastic elements k = 686.7 N / mm.

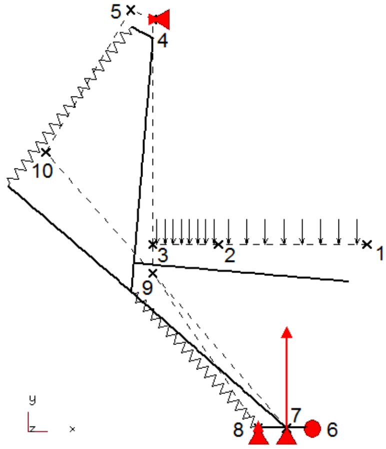

Fig. 4. In plane modeling of the bionic displacement system, SB1.

Thus, after modeling the planar structure in the numerical analysis program (finite element method) RDM 6.19 is determined, applying static analysis, the efforts in the bars and in figures 5, 6 and 7 are graphically represented the variation diagrams of the normal force N, the shear force T and the bending moment Mi and in Table 2 are explicitly specified the values of these efforts as well as the degree of functions governing their variation on each bar element.

Starting from the knowledge of the value of the forces acting in each component element of the bionic displacement system (SB1), the cross section can be dimensioned. It should be noted that this sizing calculation can be performed, in principle, from the condition of rigidity, strength and / or economy. It is recommended that only the bending moment Mi be taken into account in the pre-sizing phase.

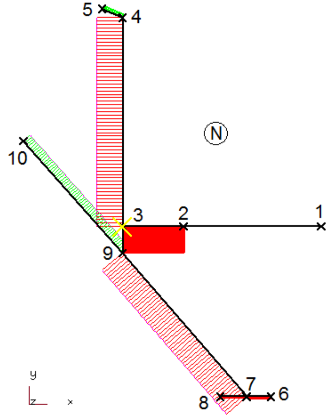

Fig. 5. Diagram of variation of the normal force N of the bionic displacement system, SB1.

The elastic elements 5-10, 8-9 can be helical traction springs (their advantage is that they occupy a relatively small space and achieve a relatively constant effect of the force applied to a large stroke) or synthetic rubber (the specific linear deformation can reach up to at 30%, their advantage is represented by the easy assembly, simple constructive form and not in the end low weight).

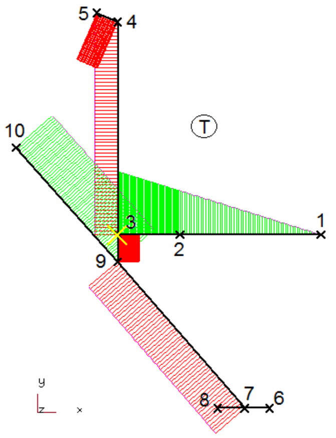

Fig. 6. Diagram of variation of the shear force T of the bionic displacement system, SB1.

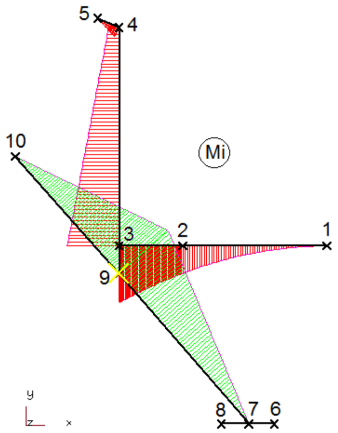

Fig. 7. Diagram of variation of the bending moment Mi of the bionic displacement system, SB1.

Table 2

N, T, Mi efforts and their distribution in the elements of the bionic displacement system, SB1 (the order of the function – OF)

interval	N [N]		T [N]		Mi [Nmm]	
1	0		0	OF:1	0	OF:2
2			475.7		-49,422.8	
2	0		475.7	OF:1	-49,422.8	OF:2
3			686.7		-103,005	
3	-472.3	OF:0	-239.4	OF:0	-93,545.7	OF:1
4	-472.3		-239.4		-18,220.9	
4	72.5	OF:0	-545	OF:0	-18,220.9	OF:1
5	72.5		-545		0	
6	-41.9	OF:0	0		0	
7	-41.9					
7	-29.5	OF:0	0		0	
8	-29.5					
9	166.7	OF:0	523.9	OF:0	117,847	OF:1
10	166.7		523.9		0	
3	-1,159	OF:0	-239.4	OF:0	-9,459.3	OF:1
9	-1,159		-239.4		0	
7	-494.9	OF:0	-411.5	OF:0	0	OF:1
9	-494.9		-411.5		117,847	

These elastic elements can have multiple geometric shapes and are made of different materials (spring steel, synthetic rubber, natural rubber but also composite materials). It is recommended to use composite materials especially when the elastic element has the shape of a curved bar in the plane.

Thus, having as reference the platform composed of the elements 1-2-3-4-5, rigidly connected, a second bionic displacement system called generic SB2 is proposed, according to Fig. 8. The length of segment 6-11 is 203.15 mm and the radius of the semicircular segment 5-7 is 396.25 mm. In nodes 6 and 11 the elements are connected by means of movable flat joints. In plane modeling of the structure of the SB2 bionic system, according to Fig. 9, allows to establish the magnitude of normal force N, the shear force T and the bending moment Mi and in Table 3 are explicitly specified the values of these efforts as well as the degree of functions governing their variation on each bar element, according to Fig. 10, Fig. 11 and Fig. 12.

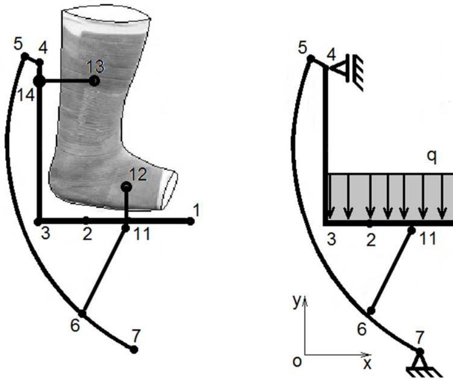

Fig. 8. Bionic displacement system, SB2.

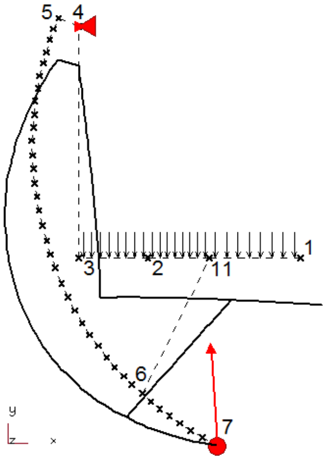

Fig. 9. In plane modeling of the bionic displacement system, SB2.

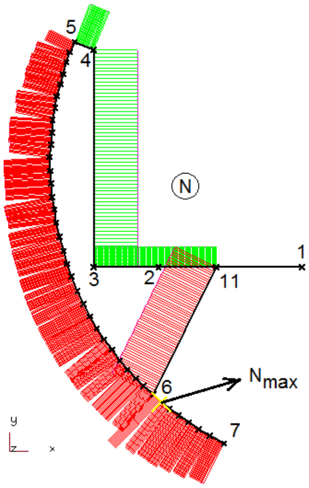

Fig. 10. Diagram of variation of the normal force N of the bionic displacement system, SB2.

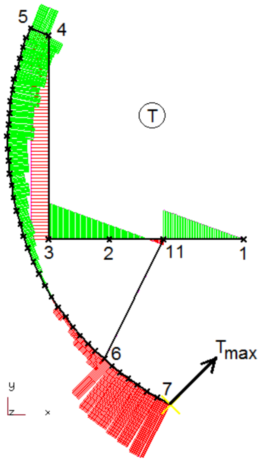

Fig. 11. Diagram of variation of the shear force T of the bionic displacement system, SB2.

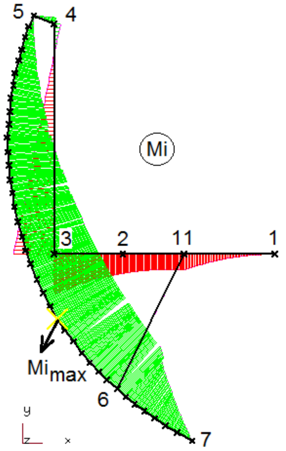

Fig. 12. Diagram of variation of the bending moment Mi of the bionic displacement system, SB2.

From the efforts diagrams (N, T and Mi) it can be seen that their maximum values are recorded in the elastic semicircular element 5 - 7 as follows: Nmax = 515.85 N, Tmax = 583.11 N and Mimax = 74,644.71 Nmm. In this semicircular elastic element variation laws governing such efforts are trigonometric functions sine and cosine.

3. RESULTS

The comparative analysis of the two proposed bionic displacement systems shows that the maximum efforts are recorded in a single element (5 - 7) in the case of SB2. From such a perspective this elastic semicircular element can be dimensioned from the strength condition using composite materials.

Table 3

N, T, Mi efforts and their distribution in the elements of the bionic displacement system, SB2 (the order of the function – OF)

interval	N [N]		T [N]		Mi [Nmm]	
1	0		0	OF:1	0	OF:2
11			280.8		-17,222.9	
11	163.4	OF:0	-50.4	OF:1	-17,222.9	OF:2
2	163.4		138.7		-20,871.1	
2	163.4	OF:0	138.7	OF:1	-20,871.1	OF:2
3	163.4		352.8		-43,852.9	
3	352.8	OF:0	-163.4	OF:0	-43,852.9	OF:1
4	352.8		-163.4		7,141.9	
4	327	OF:0	247.4	OF:0	7,141.9	OF:1
5	327		247.4		0	
6	-369.3	OF:0	0		0	
11	-369.3					

Also in the case of the bionic displacement system SB2, as a whole, the stress level is lower (NmaxSB1 = 1.159 N, TmaxSB1 = 686.7 N, MimaxSB1 = 117.847 Nmm, NmaxSB2 = 515.85 N, TmaxSB2 = 583.11 N, Mimax), according to Fig. 13.

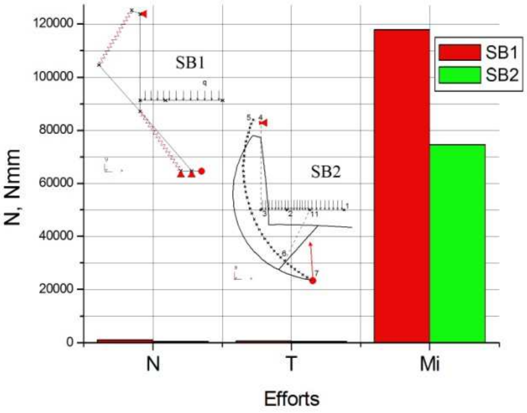

Fig. 13. Comparative analysis of the two bionic displacement systems, SB1 and SB2.

It is recommended that after sizing, regardless of the condition (strength, rigidity, economy) the elements required for compression (axial stress N is negative) to be checked for buckling.

In Fig. 14 is considered a bionic displacement system SB2 for which, in the maximum required section of the semicircular element (5 - 7), the aim is to determine the state of stress (with reference here to normal stresses σ) starting from the efforts determined numerically by the method of the element finite (topic treated in the present study) but also experimental, through the method of resistive electrical tensometry.

Fig. 14. SB2 bionic displacement system, physical model.

As a preamble of this study, which is the subject of a future paper, in Fig. 15 is the diagram of variation of the specific linear deformation (ε) in the maximum section required for the following loading scenario (called stress scenario 1): the patient, from the sitting position, rises in bipodal support after which he returns to the initial position.

4. ACKNOWLEDGEMENTS

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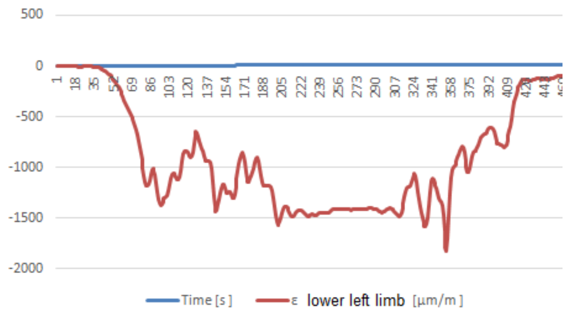

Fig. 15. Bionic displacement system SB2 in load scenario 1 - variation diagram of specific linear deformations.

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Soluţii de îmbunatăţire a mobilităţii cizmei gipsate în cazul pacienţilor cu patologii ale membrului inferior

Rezumat: *În această lucrare sunt propuse două soluții tehnice pentru îmbunătățirea mobilității cizmei gipsate în cazul pacienților cu patologii ale membrului inferior. Având ca element de referință conceptele de biomecanică și bionică, se face o analiză a principiului locomoției în regnul animal (de exemplu la cangur). Pe baza unui amplu studiu bibliografic, se definește distribuția sarcinii distribuite în zona de contact între cizma gipsată și sistemul de deplasare bionică. Folosind metoda elementelor finite, cele două sisteme bionice propuse sunt modelate cu scopul de a determina legile care guvernează distribuția eforturilor (forțelor și momentelor). Cunoscând legile variației și mărimea eforturilor, elementele care alcătuiesc aceste sisteme de deplasare bionică pot fi dimensionate optim (din condiția de rezistență, rigiditate, stabilitate și / sau economicitate).*

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