SIZE DETERMINATION OF SHOCK-ABSORBING PACKAGES OF COSTUME ELEMENT MATERIALS FOR PROTECTION AGAINST IMPACT LOADS

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Abstract: *The article defines the directions for the optimization of shock-absorbing parameters of sports and dance costume elements. The specific body movements, topography of damage and wearing were taken into account. The theoretical and practical research and substantiation of the design features of a protective costume were done on the basis of the concept about an athlete as a biomechanical system. As a result, the dimensions of the package of materials for knee pads were calculated and the recommendations concerning the design features of shock-absorbing packages for various sports and dance directions were given.*

Keywords: *sports and dance costume, biomechanical system, topography of damage, shock absorbing material packages.*

1 INTRODUCTION

Mass fashion for a healthy lifestyle increases the interest in physical activity in various kinds of sports and dances. The sports and dances where the level of dynamic loads is correlated with the level of benefit and injury prevention are gaining popularity as well as the light ones. Among such dances are Hip-Hop, Popping, Dancehall and House. In sports, these are skating, roller sports, cycling/motor sports (and acrobatic variations), skiing, marathon racing, etc. The dance sport culture is also displayed in a special costume, but in most cases injury prevention is not taken into account.

2 EXPERIMENTAL

The aim of the article is to highlight the results of calculating the parameters of universal shock-absorbing material packages for the use in designing an ergonomic and safety costume for athletes and dancers.

Biomechanical peculiarities of the human motor apparatus and a number of influential factors are determined and taken into account in the course of the studies: typical positions and movements, types of safety-designed surfaces, topography of damage and wearing of a costume during sports and dance movements.

The object of study is the design process of universal shock-absorbing elements of a costume for sports and dances.

3 RESULTS AND DISCUSSION

3.1 Preliminary analysis of the source data for calculating the parameters of shock-absorbing packages

Each of sports and dance kinds has its own peculiarities of typical body movements and positions. Choosing the main movements that characterize the biomechanics of the athlete/dancer's body, the most traumatic are the following: the frontal fall on one or both knees with different distances between the knee joints, abrupt half-splits, rotation on the shoulders, jumping on one/two feet.

When comparing static and dynamic loads on the athlete/dancer's musculoskeletal system, it has been established that the most traumatic are dynamic knee-joint loads:

- dynamic load when running (vertical component) (Figures 1 and 2): $F_{push\text{-}off}$ ≈ 1.3-2.8 kN; $F_{landing}$ ≈ 2.94 kN;
- dynamic load when falling on knee joints F ≤ 13.3 kN.

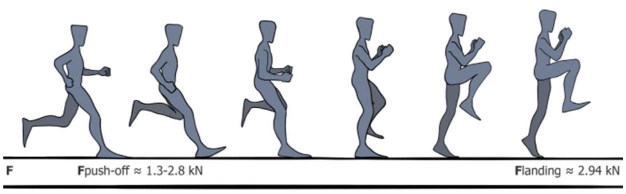

Figure 1 The forces acting on the support during push-off and landing when running

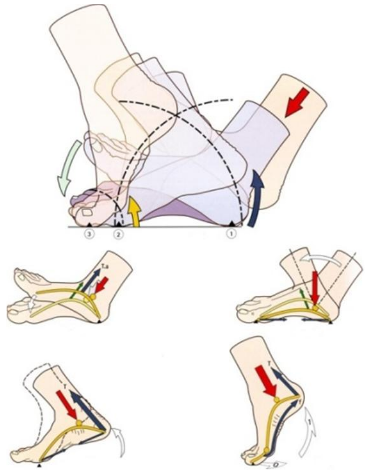

Figure 2 Four phases of the foot push-off

The types of working surfaces are of the same importance. The main of them are the following: scenic and portable sports linoleum, wooden and dance floor, vinyl surface, asphalt and concrete. Any surface can be traumatic, as each of them, depending on the type of coating, can cause different injuries. For example, the dance floor has the lowest slip friction coefficient, which in practice can lead to increased slipping and, as a result, falling of a dancer/athlete, while asphalt, with the highest slip friction coefficient, contacting with the bare areas of the athlete/dancer's body can cause skin injury.

Based on the analyzed characteristic movements and conditions of use, the topography of the athlete/dancer's body injuries and the topography of the wear of sports and dance costumes materials have been developed, and they are shown in Figures 3 and 4.

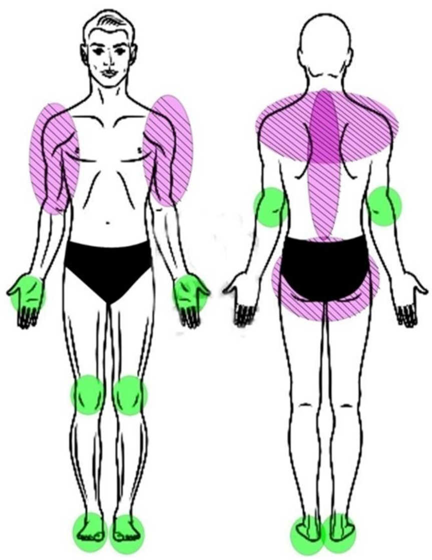

Figure 3 Topography of the athlete/dancer's body injuries
blows (hematomas, dislocations, fractures)
frictions (scratches, hematomas)

From the considered topographies of injuries, it has been found that the most injuried areas of the body are the shoulder girdle, spine, and especially, knee and elbow joints. Based on this, athletes/dancers use knee and elbow pads with an embossed surface as separate personal protective equipment (PPE) to reduce the supporting surface and impact force. When studying the special sports/dance costume design, in this work the attention is focused on the areas of knee joints as the most traumatic area.

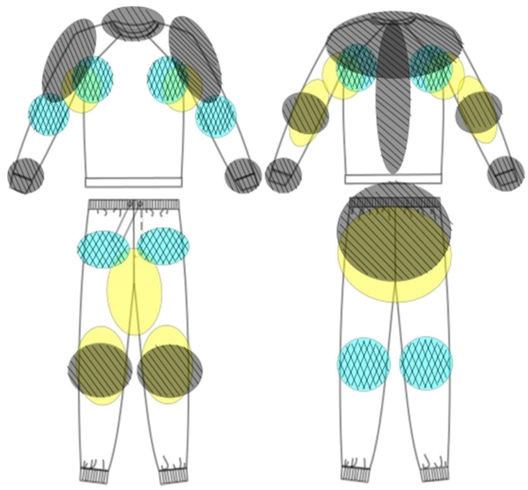

Figure 4 Topography of sports/dance costume materials wear
stretching
bending
abrasion

3.2 *Biomechanical indices of knee joints*

The study of conditions for the functioning of the human musculoskeletal system during sports and dance activities involves the identification of factors that can lead to the destruction of biomechanical systems: the study of mechanisms for improving the safety of bones, joints, muscles, ligaments, tendons; determination of the safety margin of biomechanical systems; study of adaptive mechanisms for solving specific engineering or medical problems.

The bone is a frame-mounted composite material. The mechanical properties of bone tissue depend on many factors: age, disease and individual growth conditions. The tensile strength of the bone tissue under tension σ_{tens} is 100 MPa, the relative deformation reaches 1%. In different methods of deformation (load), the bone behaves in different ways. The strength under compression is higher than while bending or stretching. Thus, the tibia in the longitudinal direction can withstand the load of 45000 N, and while bending - 2500 N. The mechanical strength of the bone is quite significant and significantly exceeds the load with which it occurs in usual living conditions.

When walking and running, during working movements of bones, gristles and joints, muscles and tendons are subjected to loading, but load in bones rarely exceeds 50 MPa. The load on the joints depends on the total weight of the body. The estimated load on the joints is expressed by the ratio of the load force to the weight of the body. At a walking speed of only 1 m/s, the load in the hip joint can reach 6 kN, which is way above the weight of the body. In sports, such acceleration is much higher, which can lead to significant, albeit short-term, loads on biomechanical systems. Thus, in time of running, the acceleration of the ankle reaches 500 m/s^2, and at the end of the impact, when performing, for example, karate tricks, even 4000 m/s^2.

It has been established that impact loads are the most injurious to the knee joint. The duration of the impact is usually 50-150 msec. In studying the process of transferring the energy of the impact through the knee joint to the thigh, it was determined that the longitudinal impact force, at which the tibia is destroyed, is from 10.6±2.7 kN (hard impact) to 18.3±6.9 kN (impact through the shock-absorbing lining).

Consequently, for sufficient protection, it is necessary to gain time and use elastic-viscous systems of supporting organs to maximize the use of shock-absorbing properties not only of technical means of protection but also of human tissues. In conventional technical materials with increased strength, as a rule, the elastic module also increases. In biological materials, all major mechanisms for increasing strength are associated with increased energy absorption. The maximum bearing capacity of bones is achieved by increasing the flexibility and raising the gradient of deformation energy growth as the load increases. Under the load above the physiological maximum, there is a significant increase in the gradient of energy gain of bone deformation.

Among the knee joint injuries, as a research object, in sports and dances, the following are common:

- injury of the collateral ligaments: elongation, partial or complete breakage of the collateral ligaments of the knee joint;

- injury of cruciate ligaments: force impact on the tibia appendages or thigh and torsion appendages (motor sports, ice hockey, football, skiing, etc.), in which the anterior cruciate ligament is 30 times more often injured than the posterior one;

- articular cartilage injury (at any joint fracture, in case of injuries with counter and compression action);

- supraclavicle fracture: as a result of direct falling on the knee or hit to the supraclavicle, less often due to excessive tension of the quadriceps muscle (transverse, less often bursting, stellate, etc. [1]).

3.3 Calculation of the parameters of shock-absorbing packages

The criterion of deformation energy density is based on two main hypotheses:

1) Destruction begins in the area where the deformation energy function has a relative constant minimum;
2) The beginning of the destruction comes at a critical for each type of material density value $(\frac{d\omega}{dv})$:

$$(\frac{d\omega}{dv})_c = \frac{S_1}{r_1} = \frac{S_2}{r_2} = ... = \frac{S_c}{r_c} = const \quad (1)$$

where S_c - the factor of the critical deformation density, which shows the impact viscosity of the material; r_c - the radius of the end of the crack, which characterizes the size of the crack, at which its rapid increase begins.

The areas in a design or material, where energy is used mainly to change the volume, but not the shape, can be identified due to this criterion. These areas are the most sensitive to the formation of cracks and, finally, the process of destruction begins in them.

Also, an important factor in the impact contact is the relative velocity (or energy) of clashing bodies, since its change during the contact determines the dependence of the contact force, local and general deformations on the time, that is, the most important characteristics of the impact in terms of mechanical and functional strength of the human body. The role of protection means against contact impact is boiled down to the reduction of these forces and deformations.

The introduction of shock-absorbing elements makes it possible to reduce the slope of the leading edge of the impact pulse, the amplitude of the contact force, and partially absorb the impact energy [2]. Consequently, research into the construction, that will ensure the safety of an athlete/dancer during training in the most dangerous cases, boils down to the determination of the type and dimensions of shock-absorbing elements to be introduced into the most damaged places.

The basis for calculating the force of the knee's impact in free fall on the flat surface and the force necessary to cause its injury is a series of developments with the simulation of cases of a person’s free fall with a certain force of contact of the head with the surface, which were conducted at the Department of Forensic Medicine MGMU named after I.M. Sechenov [3, 6].

On the basis of the given calculations, the dependence of the impact force in the process of collision of the knee with the surface on the mass, the height of the knee position before the fall and the degree of surface rigidity has been obtained, which is represented by the formula:

$$F = kP\sqrt{L} \quad (2)$$

where *F* - is the force of a knee blow during accidental fall [N]; *k* - the coefficient depending on the surface rigidity (for a rigid surface (concrete, tile, etc.) *k* = 7.7±0.6; semi-rigid (asphalt, wood, etc.) k = 5.6±0.7; non-rigid (linoleum, soil) *k* = 1.6±0.3); *P* - body weight [kg]; *L* - height of the knee position before the fall [m].

Using Newton's second law for rotation and the law of mechanical energy conservation, the angular velocity of the knee at the moment of contact with the surface can be found. Given that the initial linear velocity at accidental fall is equal to zero, we will obtain:

$$mgL = \frac{m\upsilon_x^2}{2} \quad (3)$$

where *m* - weight of the body [kg]; *g* - acceleration of free fall of the body (9.8 m/s^2); *L* - height of the knee position [m]; υ_F - final linear velocity of the knee (at the moment of impact) [m/s].

For the calculation approximating to the conditions under study, we imagine the body of the athlete/ dancer as a hinge system, and in order to simplify the task, the whole mass of the body is imagined as concentrated in one place at the point A (Figure 4). The force *F*, with which the body continues to move, and eventually, falls on the knee (or knees), is applied to the body of the dancer. For dead reckoning of the forces of the knee joint collision with the floor, the trajectory of the body motion and the directions of all the forces concerned are schematically depicted in Figure 5.

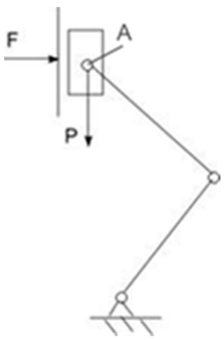

Figure 4 Scheme of fall of the athlete/dancer's body in the form of a hinge system: *F* - driving force [N], *P* - weight of the body [kg]

The following indicators were defined for solving the task: duration of falling of the athlete/dancer's body on the knee joint from the position of standing forward and sideward; duration of dancer's falling on two knee joints from th position of standing and jumping; change in the thickness of the material for inserts in the knee pads (various materials for comparison of Table 1 [4-5]); average weight of the dancer's body; height of the dancer's knee position. The necessary values for calculating the knee joint collision with the surface of the dance floor is presented in Table 2.

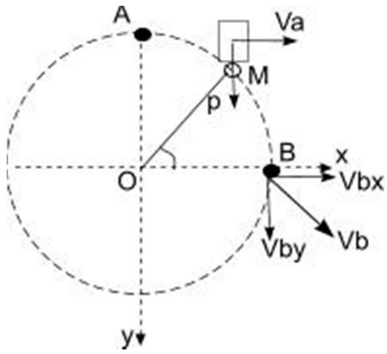

Figure 5 A diagrammatic representation of the body's fall with the distribution of forces:
A is the starting point of the body movement; M - an intermediate point on the trajectory of the body movement; B - the finishing point of the body movement; *P* - weight of the body [kg]; V_a - initial speed of the body movement; V_{bx}, V_{by} - projections of the body speed on the Ox and Oy axis [m/s]; V_b - terminal speed of the body movement [m/s]

Table 1 Thickness of materials for inserts in knee pads

Name of the laying material for the knee pads	Thickness of the material in its normal state X_0 [mm]
Batting (art. 89541)	5.80
Sintepon (art. 79604)	20.30
Thermosintepon	43.40
Laminate (art. 68134) (1 layer)	2.10
Laminate (art. 121845) (2 layers)	7.30
Laminate (art. 138483) (3 layers)	7.80
Laminate (art. 151353) (4 layers)	10.80

Table 2 Data for calculating the knee joint collision with the surface of the dance floor

Average speed of the dancer's body falling on the surface of the dance floor t_{max} [s]	0.21	
Height of the knee position *S = l* [m]	0.5	
Acceleration of free fall *g* [m/s^2]	9.8	
Average weight of the dancer's body *m* [kg]	60	
Change in the materials thickness (1-7) at the load of 60 kg, $\Delta X = X_0 - X$ [mm] (*X* - thickness of the material when loaded)	ΔX_1	4.3
	ΔX_2	18.6
	ΔX_3	35.7
	ΔX_4	1.1
	ΔX_5	5.2
	ΔX_6	4.7
	ΔX_7	5.8

Using the values from Table 2, we calculate the forces of the knee collision with the supporting surface when falling on it. We determine the speed of the knee (p. A – Figure 5) at the beginning of the movement trajectory.

$$V_A = \frac{S}{t} = \frac{0,5}{0,21} = 2,38\, m/s \quad (4)$$

We determine the knee speed at the moment of collision with the surface of the dance floor (p. B - Figure 5).

$$V_{Bx} = V_A = 2{,}38 m/s$$

$$V_{By} = \sqrt{\frac{2l}{g}} \tag{5}$$

$$V_B = \sqrt{V_{Bx}^2 + V_{By}^2} = \sqrt{V_{Bx}^2 + 2gl} = \sqrt{(2{,}38)^2 + 2 \cdot 9{,}8 \cdot 0{,}5} = 3{,}93 m/s \tag{6}$$

We determine the stiffness of each of the materials (c_n) proposed for insertion in the knee pads according to the formula (Table 3):

$$c = \frac{mV_B^2}{(\Delta x)^2} \tag{7}$$

We determine the elasticity strength of each of the materials (F_{str}) proposed for insertion in the knee pads according to the formula (Table 3):

$$F_{str} = c \cdot \Delta x \tag{8}$$

Table 3 Indicators of stiffness and elasticity of shock-absorbing materials

Indicators of stiffness [kN\m]	Stiffness index value [kN\m]	Force of elasticity [kN]	Elastic force value [kN]
c_1	51064.3	F_{elast1}	217.5
c_2	2675.7	F_{elast2}	49.8
c_3	727.9	F_{elast3}	26.0
c_4	725737.3	F_{elast4}	820.1
c_5	33750.0	F_{elast5}	176.9
c_6	410723.1	F_{elast6}	195.1
c_7	274522.6	F_{elast7}	159.5

We determine the force of the knee's impact when colliding with the supporting surface. The time of the interaction between the knee and the surface at the moment of collision we will take as 0.01 s:

$$F_{imp} = \frac{mV_B}{t_{collision}} = \frac{60 \cdot 3{,}93}{0{,}01} = 23580{,}0 H = 23{,}6 \kappa H \tag{9}$$

We determine the maximum permissable value of the knee collision force with the supporting surface and compare it with the force at which the knee joint breaks [3]:

$$F_{\max permis} = F_{str} - F_{imp} \rangle F_{breaks} = 10{,}6 \pm 2{,}7 \kappa H = 13300 H = 13{,}3 \kappa H$$

$$F_1 = 217{,}5 - 23{,}6 = 193{,}9 \kappa H \rangle F_{breaks}$$

$$F_2 = 49{,}8 - 23{,}6 = 26{,}2 \kappa H \rangle F_{breaks}$$

$$F_3 = 26{,}0 - 23{,}6 = 2{,}4 \kappa H \langle F_{breaks}$$

$$F_4 = 820{,}1 - 23{,}6 = 796{,}5 \kappa H \rangle F_{breaks}$$

$$F_5 = 176{,}9 - 23{,}6 = 153{,}3 \kappa H \rangle F_{breaks}$$

$$F_6 = 195{,}1 - 23{,}6 = 171{,}5 \kappa H \rangle F_{breaks}$$

$$F_7 = 159{,}5 - 23{,}6 = 135{,}9 \kappa H \rangle F_{breaks}$$

Therefore, the forces of knee joint collision with the surface using any of the suggested pads, except for Sample No. 3 (thermosintepon), will be less than the force of knee joint destruction itself. That is, for the safety of the athlete/dancer, you can use any of the selected materials for knee pads, except for thermosintepon, based on the aesthetic value only (Figure 6).

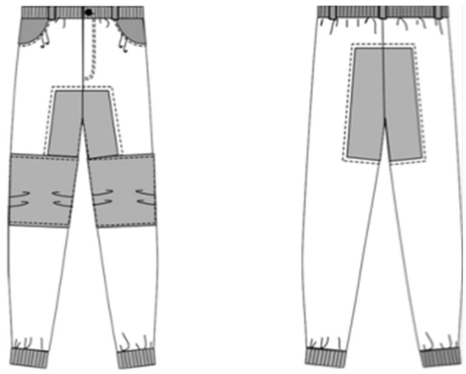

Figure 6 Design of pants with sewn-in shock-absorbing knee pads

Athletes/dancers usually use knee pads as separate personal protective equipment for workouts or performances, wearing them under their pants. However, the procedure for putting them on together with pants requires twice as much time and somewhat more efforts, moreover, separate knee pads increase the cost of the set [7-9]. Thus, in order to provide an aesthetic appearance, as well as proper safety of the dancer/athlete, it is proposed to introduce knee pads, sewn into pants, made of the material with high shock-absorbing properties and with a relatively small thickness. Laminate, which is sewn into pants in two layers, was chosen as such a material according to the research. This will allow to save time putting on supplementary PPE and reduce the cost of the set.

4 CONCLUSION

The obtained calculations can be recommended for determining the parameters of shock-absorbing overlays when designing clothes for different types of physical activity for knee and elbow joints, ischial bones, etc.

5 REFERENCES

1. Gromov A., Naumenko V.: Forensic Traumatology: a guide, Moscow, The Medicine, 1977
2. Obraztsov I., Adamovich I., Barer A.: Problems of strength in biomechanics, Textbook for technical. and biol. specialist. Universities, Moscov, The High School, 1988
3. Optimization of diagnostics of the mechanisms of head injury when falling onto a plane, Collection of plenary and poster reports of the All-Russian Scientific and Practical Conference with international participation, dedicated to 75th anniversary of the RC SME, Moscow, 2006, pp 273-278

4. Yamaguchi J., Takanishi A., Kato I., Experimental development of a foot mechanism with shock absorbing material for acquisition of landing surface position information and stabilization of dynamic biped walking, Proceedings of 1995 IEEE International Conference on Robotics and Automation, Nagoya, Japan, 1995
5. Dolzhenko M., Garkavenko S, Babich A.: Investigation of physical-mechanical characteristics of leather materials in the process of manufacture and operation of footwear, Bulletin of the Kiev National University of Technology and Design 2, 2017 http://nbuv.gov.ua/UJRN/td_2017_2_10
6. Pervaia N., Andreyeva O., Maistrenko L.: Rational use of natural polymer materials for the manufacture of footwear, Baltic Polimer Symposium 2018 (BPS 2018), Jurmala, Latvia, September 12-14, 2018, p.107
7. Gemperle F., Kasabach C., Stivoric J., Bauer, Martin R.: Design for wearability, Digest of Papers., Second International Symposium on Wearable Computers (Cat. No.98EX215), Pittsburgh, USA, 1998
8. Omelchenko G., Kolosnichenko M.: Backgrounds for the development of children's multifunctional clothes of protected dempper elements, II International Scientific and Practical Conference "The current state of the light and textile industry: innovention, efficiency, environmentality", Kherson, Ukraine, 2016, 91-93 pp
9. Ivasenko M., Ermakova M., Orenchina Ya.: Outdoor dance clothes, as part of a dancer's biomechanical system, Light industry 4, 2013, pp. 77-79