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O. V. Pogrebnoy

MODELING OF ELEMENT DAMAGE OF BIOMECHANICAL SYSTEM UNDER ACTION OF EXTERNAL FORCE FACTORS

The radiocarpal joint of wrist is regarded as a biomechanical system. The influence of external force factors of different intensity on the biomechanical system is investigated. The initial data of this study is a wide amount of roentgenograms of damaged elements of this system. Each case of injury is classified with regards to the types of an international classification system. The influence of gender factor on distribution of patients quantity in dependency of fracture type is studied by the non-parametrical statistics methods. The dependencies of fracture type from a patient age are found.

Keywords: *modeling, biomechanical system, radiocarpal joint, radius, osteoporosis, type of fractures, roentgenogram, bone tissue fracture, non-parametrical statistics.*

Introduction. The radiocarpal joint is an important part of human wrist and forms a complex biomechanical system. Making different functions in human life, this joint is subjected to an action of external forces and an influence of some internal factors, that weak its strength properties. The internal factors consist of different kind deceases, for example, osteoporosis, and time factor.

The radiocarpal joint anatomy has being studied from the ancient time. As an example of modern comprehensive issue, concerned to the physiology of joints, it is necessary to mention [6]. There is quantity of modern universal foreign and created in time of USSR and after guides, in particular, [1, 2, 26, 27]. The anatomy and biomechanics of the radiocarpal joint were investigated, for example, in [13, 15, 16, 18, 20, 25, 28, 29]. The mechanical properties of proximal radius bone tissue were determined in [9].

The time factor, internal property of the biomechanical system, has an essential influence on material weakening that leads to mechanical strength decrease. One of the revealing of such process is a decrease of bone tissue entirety, in our case it is a pore increase in distal radius. The time factor influence on the particularities of wholeness injury of the biomechanical system was studied in [16, 18, 24]. Some problems of recovery of system functionality and values of rehabilitation methods were investigated in [12, 14].

The most widespread method for investigation of bone tissue structures is well-known method of roentgenogram analysis, that was used, particularly, in [15, 16, 19, 24]. The latest years the powerful and perspective method of computer tomography receives significant popularity [13, 21, 22].

The problem of working-out of universal classification of bone fractures was investigated, in particular, [3, 4, 7, 10, 11].

In present paper the modeling of element damage of biomechanical system with taking into account an influence of external force and internal factors is fulfilled.

Object of investigation. The radiocarpal joint (articulation radiocarpea) is regarded as biomechanical system, i.e. junction of radius joint depression and of wrist first rank three bones: scaphoid (os scaphoideum), lunare (os lunatum), and triquetrum (os triquetrum) (Fig 1). The distal radius, which damages are studied here, has the most part of contact with scaphoid. The elbow bone (ulna) does not have a contact with the radiocarpal joint, and has a junction with the fibrous-cartilage disk (ligament triangularae). The radiocarpal joint is strengthened by next ligaments: lateral collaterial, ulnal collaterial, palmar ulnocarpal, dorsal radiocarpal, palmar radiocarpal and interosea ones. The radiocarpal joint is classified: by complexity as complex, by form as elliptical, by function as biaxial joint. In the radiocarpal joint two types of motions are realized: bending - unbending and leading – deflection.

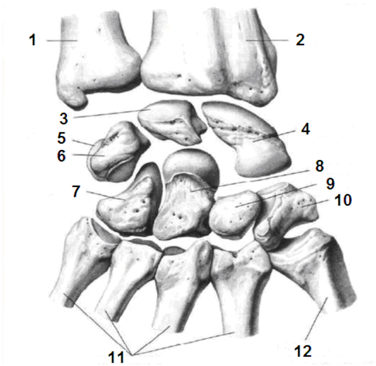

Fig. 1 – **Radiocarpal joint**

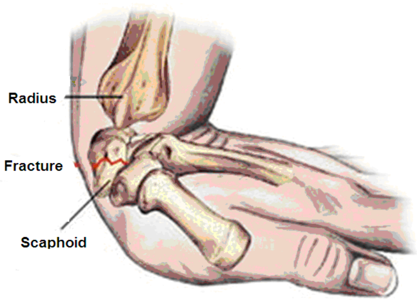

Fig. 2 – **Dorsal overunbending in radiocarpal joint**

On the Fig. 1 next labels were used: 1 – elbow bone (ulna), 2 – radius (spoke) bone (radius), 3 – semilunar (lunate) bone (os lunatum), 4 – scaphoid (navicular) bone (os scaphoideum), 5 – postlunar bone (os pisiforme), 6 – cuneiform (pyramidal) bone (os triquetrum), 7 – hamate (unciform) bone (os hamatum), 8 – capitate bone (os capitatum), 9 – trapezoid bone (os trapezoideum), 10 – trapezium bone (os trapezium), 11 – carpal bones (ossa metacarpalia), 12 – carpal bone I (os metacarpale I).

The main mechanism of wholeness injury of studied biomechanical system is dorsal over-unbending in the radiocarpal joint. The most frequent type of damage is radius fracture in typical place – Colles' fracture. The scheme of dorsal over-unbending of the wrist and, as consequence, a wholeness injury (fracture) of one element of the biomechanical system, namely the scaphoid bone is presented on Fig. 2.

Besides the action of external forces the studied biomechanical system is subjected to an influence of internal time factor – human age. The osteoporosis – decease of aged people leads to increase of porous of trabecular (sponge) bone. The mechanical strength decrease especially under dynamic loading is a consequent of such phenomenon. So in medical practice the notion of high- and low-energetic trauma is used. The high-energetic trauma takes place, obviously, under an action of external force factor of high intensity, for example, a fall from height of several meters. The advanced stage of osteoporosis may leads to appearance of the low-energetic trauma, such as a fall from human own height [7].

In 1981 year ASIF (Association on study internal fixation) accepted the AO fracture classification (Association of an osteosynthesi) according to the ABC system [3, 10]. The AO classification was based on division into type, group and subgroup that further describe a fracture level and localization, its distance from joint and bone fragment displacement. From 1990 year an additional AO classification that named the Universal fracture classification is acting [3, 11]. The main principle of this classification is determination of type, group and subgroup of fracture of each bone with damage in detail. The hierarchical division of fractures, typical for any distal segment of long bone, into three types and 27 subgroups is presented in Fig. 3 [7].

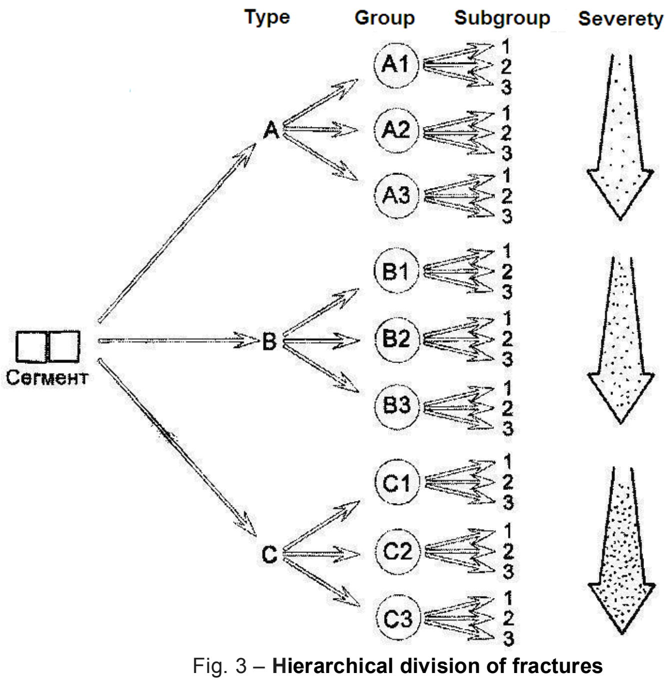

Fig. 3 – **Hierarchical division of fractures**

Three types of fractures of any bone segments are marked by capital letters A, B and C. Each type is subdivided into three groups marked by letters with Arabic digits (A1, A2, A3, B1, B2, B3, C1, C2, C3). The damages of group A1 are the most simple with the best prognosis and ones of group C3 are the worst injures with the bad prognosis.

The anatomical localization is marked by two digits: first for bone, second for its segment. Each bone or bone group is marked by digits from 1 to 8: 1 – shoulder bone; 2 – radius and elbow bone; 3 – femoral bone; 4 – shin-bone and calf bone; 5 – spinal (vertebral) column; 6 – hip bones; 7 – wrist bones; 8 – foot bones. All remaining bones are classified by digit 9: 91.1 – patella; 91.2 – collar bone; 91.3 – shoulder-blade; 92 – lower jaw; 93 – face and skull bones.

Each long bone consists of three segments: proximal, diaphyseal and proximal. Any fracture with displacement of fragment with part of join surface is intra-articular one. If fracture without displacement contains a crack that reaches the join surface, it is classified as metaphyseal or diaphyseal [7].

The fracture types of long bone diaphyseal segments are identical: simple fractures (type A), or comminuted ones. The comminuted fractures may be cuneate (type B) or complex (type C) in dependency of contact between segments after reposition (Fig. 4).

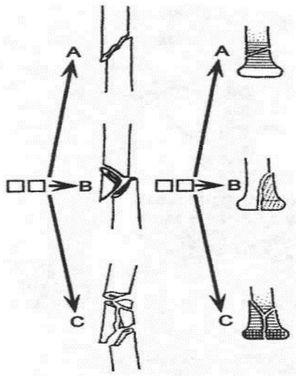

Fig. 4 - **Types of fractures**

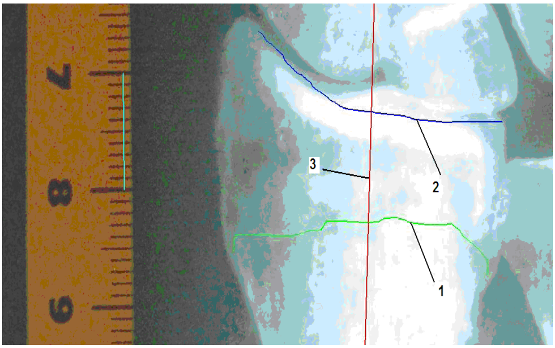

Fig. 5 - **Radius fracture in typical place**

Three fracture types of distal segments (13-, 23-, 33-, 43-) and two from four proximal segments (21-, 41-) are identical. It is near-joint fractures (type A) or inner-joint fractures that classified as non-entire fractures (type B) and entire ones (type C).

The fracture localization of long bones and hip ones are marked by two digits. Letter, placed after, and else two digits describe the fracture morphology. The example of classification of distal segment fracture that is presented on Fig. 5: 23-A2.1, where (from left to right) 2 – radius and elbow bone; 3 – distal segment; A – near-joint fracture of radius; 2 – simple near-joint fracture; 1 – metaphiseal fracture.

On Fig. 5 the part of roentgenogram with marked structural elements and scale is presented [15, 24]. Here next structural elements are marked by digits: 1 – fracture line; 2 – joint surface; 3 – radius axis.

It is important to note occurs or not the complex damage of radioulnar joint when the distal segment fracture of radius or elbow bone takes place with the aim to mark the non-entire fractures (type B) and the entire ones (type C).

As in the paper only the fractures of radius distal segment will be studied, the index "23" before the fracture types A, B and C is omitted.

Objective of investigation. The modeling of wholeness injury of the biomechanical system elements with taking into account the internal (gender, age) and the external (intensity of traumatic factor) factors is an objective of this study.

The non-parametrical statistical methods [5, 8] were used in this study.

Problem statement. The distribution of patient quantity depending on fracture type and its relative values with taking into account the gender factor is presented on table 1.

Table 1 – **Distribution of patient quantity according fracture types**

№	Fracture type	Patient quantity		Relative values	
		Women	Men	Woman	Men
1	2	3	4	5	6
1	A2.1	62	13	0,45	0,65
2	A2.2	138	20	1	1
3	A2.3	2	0	0,014	0
4	A3.1	17	1	0,123	0,05
5	A3.2	1	2	0,007	0,1
6	A3.3	2	1	0,014	0,05
7	B1.1	4	3	0,029	0,15
8	B1.3	1	0	0,007	0
9	B2.1	4	0	0,029	0
10	B3.2	1	0	0,007	0
11	B3.3	1	0	0,007	0
12	C1.2	6	2	0,043	0,1
13	C1.3	0	2	0	0,1
14	C2.1	18	1	0,13	0,05
15	C2.2	7	1	0,051	0,05
16	C2.3	2	1	0,014	0,05
17	C31	1	0	0,007	0
18	C3.2	2	0	0,014	0
19	C3.3	2	0	0,014	0
Total	–	271	47	–	–

The radiocarpal joint (Fig. 1) regarded as a biomechanical system is under action of external force factors. A wide amount of roentgenograms, namely 318, of patients with damages of radius distal metaphysic is the initial experimental data for investigation of an influence of internal factors and of an action of external ones of different intensity. There are 271 roentgenograms of women and 47 ones of men. The men age varied from 20 to 77 years with average value 48,32. The women' age is in limits from 20 to 84 with average 56,33. Note essential dimorphism in patient quantity: the ratio of men' quantity to women one is 1 to 5.77. For men patient 11 fracture types were classified according to AO/ASIF [7]. For women were classified 18 fracture types.

The more detailed description of fracture types from column 2 of table 1 is in [7], chapter 1, part "Main fracture types of skeleton bones".

The patient quantity of both sex were calculated for each classified fracture types. After that the relative patient quantity (column 5 and 6 from table 1) were calculated by division the values from column 3 and 4 by maximal values for women (138) and men (20), respectively. Note that maximal absolute and, consequently, relative values concerned to A2.2 fracture type.

Results and its analysis. On the base of the data from in table 1 the dependencies between fracture type and relative patient quantities for woman and men are constructed and presented on Fig. 6. Both dependencies reach their maximums for A2.2 fracture type. For the fractures from range A2.3–C3.3 the relative values do not exceed 0.13 and 0.15 for women and men, respectively.

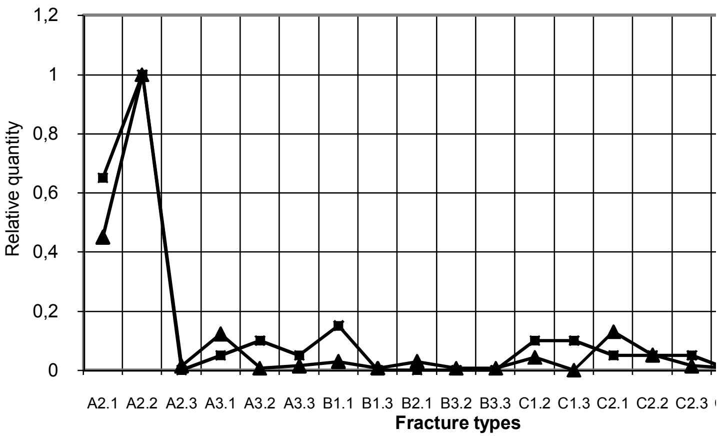

Fig. 6 – **Dependencies between fracture types and relative quantities of female patients and male ones**

For revealing existing differences into the dependencies of patient quantities and fracture types for female and male samplings it is possible to use the biserial correlation coefficient. By this coefficient the closeness of dependencies between qualitative characteristics with two variants and quantitative characteristics may be measured [8]:

$$r_{bs} = \frac{\bar{x}_1 - \bar{x}_2}{s_x} \sqrt{\frac{n_1 n_2}{N(N-1)}} ,$$

where $\bar{x}_1$ and $\bar{x}_2$ are arithmetic average of alternative groups with volumes n_1 and n_2 ; $N = n_1 + n_2$ total observation value or sampling value; s_x is average quadratic deflection of the whole sampling.

In our case the alternative groups are the relative values of female and male patient quantities in dependency on the fracture types, i.e. columns 5 and 6 of the table 1; volumes are $n_1 = n_2 = 19$, $N = n_1 + n_2 = 19 + 19 = 38$; average quadratic deflection of the whole sampling is $s_x = 0.4961$. Hence the biserial correlation coefficient is r_{bs} =0.021.

The validity of the biserial correlation coefficient is appreciated by the use of Student t -criterion with degree of freedom number $k = N - 2 = 36$ by formula

$$t = \frac{r_{bs}\sqrt{k}}{\sqrt{1 - r_{bs}{}^2}} .$$

Substituting values r_{bs} and k we obtain t =0,021.

The value of validity criterion t does not exceed a critical level t_{st} =2,02 with α =0,05 and k =36. Hence, the zero-hypothesis H_0 does not rejected with the validity level 5% ($P > 0,05$).

The obtained result proofs that in spite of essential dimorphism in patient quantity, the substantial differences in the distribution of the patient quantity in dependency of fracture types do not revealed.

The distribution of fractures quantity in dependency on patient age is studied in 10-th year intervals: 20÷29, 30÷39, 40÷49, 50÷59, 60÷69, 70÷79 and 80÷89 years.

The fracture types are qualitative characteristics, so to each fracture type a conditional rank with characteristic decreasing order is given [5]. Two methods of ranking ratings are used: for detailed classification AO/ASIF and for simplified approach that includes the types A, B and C only and describes the fracture position with respect to the joint. The fracture types with corresponding ranks are presented in table 2.

The data about the distribution of female patient quantity, average ranks and the fracture distribution in types A, B, C according to the age intervals are presented in table 3. The average ranks of the classification AO/ASIF and types A, B, C are calculated as arithmetic average of fracture ranks according to table 2.

Table 2 – **Ranking rating of fracture types**

№	Fracture type	Rank AO/ASIF	Rank A,B,C
1	A2.1	1	1
2	A2.2	2	1
3	A2.3	3	1
4	A3.1	4	1
5	A3.2	5	1
6	A3.3	6	1
7	B1.1	7	2
8	B1.3	8	2
9	B2.1	9	2
10	B3.2	10	2
11	B3.3	11	2
12	C1.2	12	3
13	C2.1	13	3
14	C2.2	14	3
15	C2.3	15	3
16	C3.1	16	3
17	C3.2	17	3
18	C3.3	18	3

The histogram of female patient distribution in the age intervals (columns 2 and 3 of table 3) is presented in Fig. 7. The maximum quantities of female patients in almost equal values are in the age intervals of 50÷59 and 60÷69 years.

The histogram of fracture distribution in types A, B, C according to the age intervals (columns 2, 6, 7 and 8 of table 3) is presented in Fig. 8. The fracture of type A are of most frequency and reaches its maximum in the age interval of 50÷59 years.

Table 3 – **Data about female patients, distributed in age intervals**

№	Age intervals	Patients quatity	Average rank AO/ASIF	Average rank A, B, C	A	B	C
1	2	3	4	5	6	7	8
1	20-29	5	6	1,8	3	0	2
2	30-39	26	5,15	1,54	19	0	7
3	40-49	39	1,97	1	39	0	0
4	50-59	81	3,28	1,25	70	2	9
5	60-69	82	4,2	1,37	64	6	12
6	70-79	26	5,19	1,54	18	2	6
7	80-89	12	4,67	1,42	9	1	2
					222	11	38
Total	–	271	–	–	A + B + C = 271		

The dependences of fracture average ranks according to the classification AO/ASIF and types A, B, C are presented in Fig. 9.

The average rank values of the age intervals of 20÷29 and 30÷39 correspond, obviously, to the high-energetic trauma. Moreover, the average rank maximum in the age interval of 20÷29 years may be explained by small patient quantity, so, this value is of insufficient reliability.

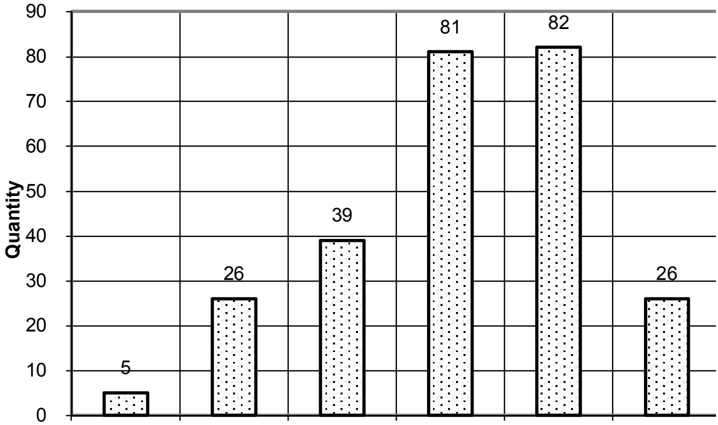

Fig. 7 - **Distribution of female patients in age intervals**

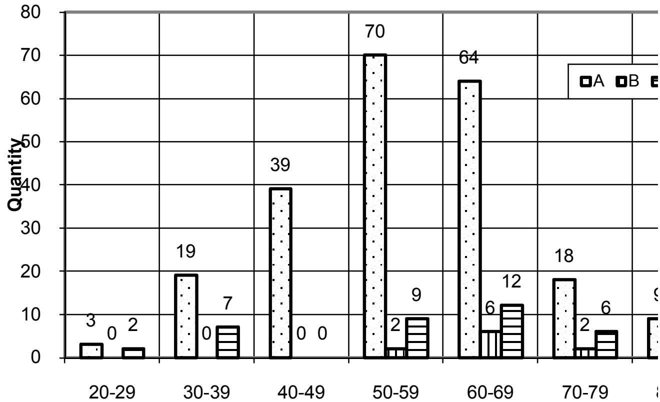

Fig. 8 – **Distribution of female patient fractures of types A, B, C in age intervals**

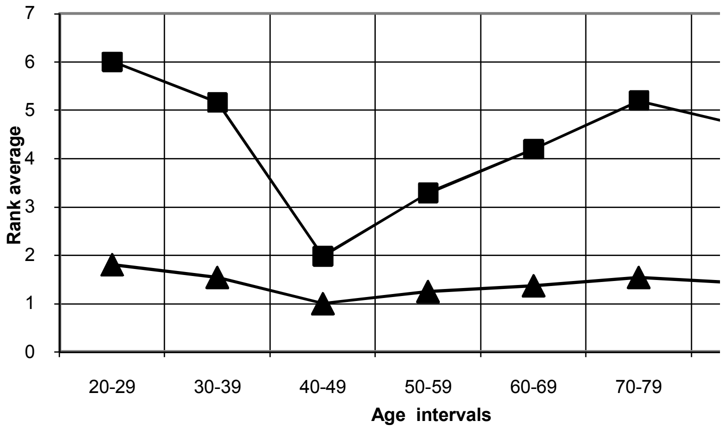

Fig. 9 - **Dependences of fracture average ranks according to classification AO/ASIF and of types A, B, C**

It is well-known that the osteoporosis as systematic deceases reveals, as a rule, after 50 years [14]. The dependence of average ranks from patient ages for senior women (beginning from 50 years inclusively) is studied. The data of the age interval of 40÷49 years are taking into account.

The dependences of average ranks according to the classification AO/ASIF (upper and marked by squares) and of types A, B, C (lower and marked by triangles) are presented in Fig. 10. The equation of trend line for the upper dependence is $y = -0.25x^2 + 2,2652x + 0,1173$ with the coefficient $R^2 = 0,9706$. The respective equation for lower dependency is $y = -0.0488x^2 + 0,4055x + 0,6343$ with $R^2 = 0,9594$. It can be noted that for description of the average rank A, B, C (lower dependence) the linear trend may be useful: $y = 0,1125x + 0,9761$ with $R^2 = 0,7591$.

The data of table 3 and the plots in Fig. 10, described by the equations, proof the tendency of monotone increase of average ranks AO/ASIF and A, B, C with monotone increase of female patient age. With taking into account the basic principle of fracture division into the main types A, B, C, it can be stated an existence of the phenomenon of fracture line shift towards the joint surface in dependency of age increase for female patient. The obtained result corresponds with the conclusion of other morphometrical investigations [15, 21].

The dependence of fracture type according to the classification AO/ASIF from male patient age is presented in Fig. 11.

The obtained dependence is described by linear trade $y = 2.0586x + 39.157$ with $R^2 = 0,3436$. It demonstrates that presence of fractures types B and C of male patients linearly depended from its age.

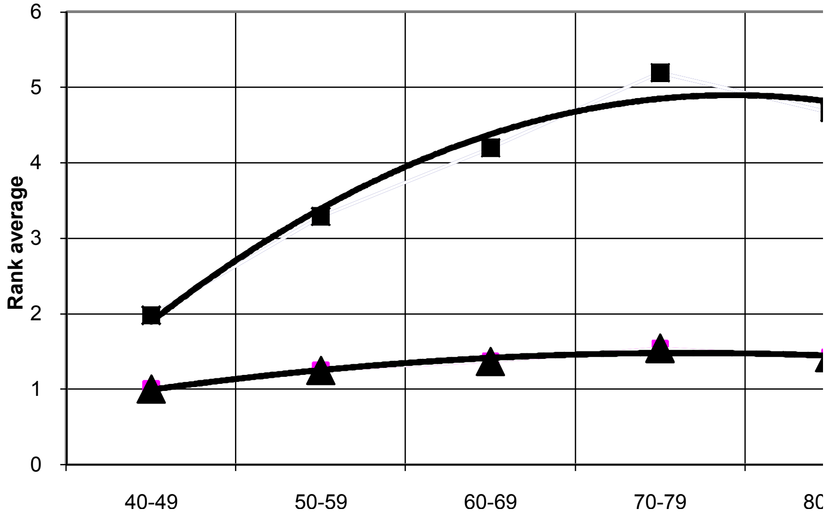

Fig. 10 – **Dependences of average ranks according to classification AO/ASIF and types A, B, C from age intervals for senior women**

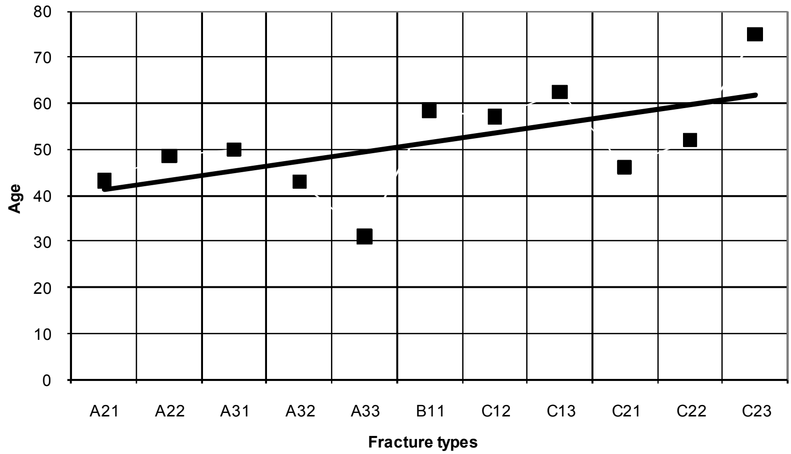

Fig. 11 - **Dependence of fracture types according to AO/ASIF from male patient age**

Conclusions. The modeling of biomechanical system properties by non-parametrical statistical methods is fulfilled. The radiocarpal joint is regarded as studied biomechanical system under action of external forces, taking into account some morphological changes in bone tissue and an influence of gender factor. The following results are obtained.

1. The relationship between the shift in distal direction of fracture line of radiocarpal joint and the age increase of female patient from aged group, that described by quadratic equation is established.

2. The dependency between the age increase of male patient and the fracture type of radiocarpal joint, that described by linear equation is revealed. This dependency takes place with partial and full inner-joined fractures.

3. The injury of wholeness/entirety of biomechanical system material occurs, evidently, as a result of action of force (traumatic) low-intensity factor, i.e. the low-energy trauma takes place.

4. The considerable influence of gender factor on the distribution of patient quality according to fracture types, despite the fact of essential gender dimorphism, was not revealed using the non-parametrical statistical methods.

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О. В. Погребной

МОДЕЛИРОВАНИЕ НАРУШЕНИЯ ЦЕЛОСТНОСТИ ЭЛЕМЕНТОВ БИОМЕХАНИЧЕСКОЙ СИСТЕМЫ ПРИ ВОЗДЕЙСТВИИ ВНЕШНИХ СИЛОВЫХ ФАКТОРОВ

На основании обширного экспериментального материала исследовано поведение биомеханической системы, в качестве которой выступал лучезапястный сустав, при воздействии на неё внешних силовых факторов различной интенсивности. Первичными экспериментальными данными являлись рентгенограммы поврежденных участков биомеханической системы. Для каждого рассматриваемого случая проведена классификация типа нарушения целостности элементов системы. Методами непараметрической статистики изучено влияние гендерного фактора на распределение количества пациентов по типам переломов. Получены зависимости типа перелома от возраста пациентов.

Ключевые слова: *моделирование, биомеханическая система, лучезапястный сустав, лучевая кость, остеопороз, типы переломов, рентгенограмма, разрушение костной ткани, непараметрическая статистика.*

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О. В. Погрібний

МОДЕЛЮВАННЯ ПОШКОДЖЕННЯ ЩІЛЬНОСТІ ЕЛЕМЕНТІВ БІОМЕХАНИЧНОЇ СИСТЕМИ ПІД ВПЛИВОМ ЗОВНІШНІХ СИЛОВИХ ФАКТОРІВ

На підставі обширного експериментального матеріалу досліджено поведінку біомеханічної системи, зокрема. лучезап'ясний суглоб, при дії на нього зовнішніх силових факторів різної інтенсивності. Первинними експериментальними даними були рентгенограми пошкоджених ділянок біомеханічної системи. Для кожного випадку проведено класифікація типу порушення щільності елементів системи. Методами непараметричної статистики вивчено вплив гендерного чинника на розподіл кількості пацієнтів за типами переломів. Отримано залежності типу перелому від віку пацієнтів.

Ключові слова: *моделювання, біомеханічна система, лучезап'ясний суглоб, променева кістка, остеопороз, типи переломів, рентгенограма, руйнування кісткової тканини, непараметрична статистика.*

Дніпровський національний
університет імені Олеся Гончара,
Дніпро, Україна

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