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The Methodology of Diagnostics, Rehabilitation and Improvement of Muscles of The Locomotor System on The Training Systems.

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ABSTRACT

The purpose of this methodology is the ability to determine the degree of injury of each muscle of the locomotor system by technical means. Existing methods that are using modern technical means allow establishing the disease of the muscular unit or group of muscles that are performing a specific movement type. This methodology is based on experimentally-theoretical approach. Experimental and theoretical methodology consists of several stages: definition of the area of the disease of the muscular system; the selection of types of movements to the body of the patient; the choice of trainers, which can not only carry out a selected movement, but to a more specific group of muscles, to carry out these movements; in the absence of the device in the training system that is registering the force produced by the muscles, we offer the retrofit of the training system by the measuring devices. The next stage – on the training device at a given movement we define a maximum force produced by a muscle group (the resultant force). The last stage consists of a mathematical processing of experiment results to assess the condition of each muscle involved in a given movement. The result of this work is the ability to diagnose each muscle of a musculoskeletal system using automated and semi-automated training systems, and common mechanical systems. We have proposed a variant of modernization of the mechanical system, which will simplify diagnostics and rehabilitation for diseases of the musculoskeletal apparatus. In addition, sport-trainers can use this technique to prepare elite athletes.

Keywords: experimentally-theoretical method, diagnostics of every muscle, the formula for muscle power, the modernization of the mechanical training systems

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INTRODUCTION

All motor activity of man is carried out with the help of musculoskeletal system. The system of the musculoskeletal apparatus constitutes the bones, ligaments, joints and muscles. Bones, ligaments and joints are passive elements of the movement. Active portion of the apparatus of the movement are muscles. The muscular system consists of skeletal muscles, tendons and ligaments. About 12% of the populations of the planet have the diseases of the musculoskeletal system. Many diseases of the musculoskeletal apparatus occurring chronically and often lead to disability, so their treatment is one of the topical issues of modern medicine [1, 2].

In the paper [3] we showed an example of the possibility of upgrading a relatively inexpensive bike for the diagnosis of specific lower limb muscles. In this work is presented a technique of selecting of necessary training system (if you need inexpensive modernization) to determine a disease of certain muscles or the extent of their damage.

There are well known methods aimed at studying the functional state of the joints of the patient evaluation scale d`Aubigne and Poste [4] and Harris [5]. These systems define pain, gait disturbance, functional ability in daily life. Their disadvantage is the possibility of dependence on the human factor, which is able to result in a depressed psycho-emotional state of the patient etc.

The well-known method of visualization of the muscles in computed tomography (CT) with applying of a contrast agent "Omnipak" allows reliably studying the structure and nature of morphological changes in the muscle during the development of pathological conditions [6], "A method of visualization of muscles in computed tomography". The disadvantage of this method is the invasiveness, due to the required use of contrast, the impossibility of determining the density of muscles and comparing the indicator from the opposite side.

A method of assessing atrophy of the thigh muscles with contractures of hip and knee joints [7] is followed by multiplanar reconstruction in axial, paraxial and transverse planes in the region of the hip joints, thighs, by studying the thickness, density cross sections in specific densitometric Hounsfield units (HU) and compared with the intact segment. The disadvantage of this method is the high complexity of the process of multi-planar reconstructions in different planes, which leads to a significant increase in CT scans and as a consequence, to the increase in radiation exposure.

Is known a method of assessing the functional result of treatment after total hip replacement [8], which consists in using a single indicator that expresses the functional activity of the patient by visualization of a single-joint muscles of the hip joint on CT scan, with the use of quantitative assessment of changes in their structure. Are measured the area and density of muscle tissue in the specific densitometric Hounsfield units (HU) in symmetric divisions, then is determined the coefficient of atrophy as the ratio of sums of products of the area and density of the muscles of the healthy side to the sums of multiplications of squares and densities of the investigated muscles of the affected side of the body. The disadvantage of this method is an indirect determination of the coefficient of atrophy by comparing data for healthy and pathological sides of the body. In the pathology of both sides obtaining of the objective data about the functional state is impossible.

THE MAIN PART

Modern training systems are expensive and difficult to operate, so they are available only in large medical institutions [9]. In addition, they have no method of determining the disease of a specific muscle. In this paper, on the example of modernization of the training equipment is carried out a study of pathologies and creation of the device for diagnostic, rehabilitation and athletic performance enhancement. While developing was used the following devices: "Biodex System 3Pro" and "CON-TREX" [10, 11]. The developed unit is designed not only for the diagnosis and rehabilitation of patients, but also for training highly qualified athletes. Training on the device is able to improve the overall physical condition of the body.

When the patient's pathology appears in a specific muscle group, it should be determine the type of movement involving the muscles of this group. Based on this, it is necessary to find a training apparatus which would involve this muscle group in a work [12, 13]. And by means of experimental-theoretical method a diagnostic will be carried out with a help of simulator, which will identify an individual muscle with pathology. Table 1 presents the major muscles in the musculoskeletal system involved in the mechanical movements of the person.

Table 1. Muscles of locomotor apparatus

Number	Muscle	Musculi
1	Sternocleidomastoid	M. sternocleidomastoideus
2	Sterno-hyoid	M. sternohyoideus
3	Trapezoidal	M. trapezius
4	Sterno-thyroid	M. sternothyroideus
5	Deltoid	M. deltoideus
6	The pectoralis major muscle	M. pectoralis major
7	Latissimus dorsi	M. latissimus dorsi
8	Arm triceps	M. triceps brachii
9	Biceps muscle of the arm	M. biceps brachii
10	Shoulder muscle	M. brachialis
11	The brachioradialis muscle	M. brachioradialis
12	Long radial extensor muscle of wrist	M. extensor carpi radialis longus
13	Round pronator	M. pronator teres
14	Short radial extensor muscle of wrist	M. extensor carpi radialis brevis
15	The radial flexor of the wrist	M. flexor carpi radialis
16	Long palmar muscle	M. palmaris longus
17	Superficial flexor of the fingers	M. flexor digitorum superficialis
18	Ulnar flexor of the wrist	M. flexor carpi ulnaris
19	The serratus anterior muscle	M. serratus anterior
20	Abdominal external oblique muscle	M. obliquus externus abdominis
21	The rectus abdominis	M. rectus abdominis
22	The upper front iliac spine (bone)	Spina iliaca anterior superior
23	Iliac muscle	M. iliocostalis
24	Muscle tensioning fascia lata	M. tensor fasciae latae
25	Psoas major muscle	M. psoas major
26	Pectineus muscle	M. pectineus
27	Adductor magnus muscle	M. adductor magnus
28	Thin muscle	M. gracilis
29	Rectus femoris muscle	M. rectus femoris
30	Adductor longus muscle	M. adductor longus
31	Sartolius muscle	M. sartorius
32	Medial vastus	M. vastus mediales
33	Vastus lateralis muscle of the thigh	M. vastus lateralis
34	Ilio-tibial tract	Tractus iliotibialis
35	Patella	Patella
36	Patella ligament	Ligamentum patellae
37	Calf muscle	M. gastrocnemius
38	Tibialis anterior muscle	M. tibialis anterior
39	Long extensor of the toes	M. extensor digitorum longus
40	Long peroneal muscle	M. peroneus longus
41	Flexor digitorum longus	M. flexor digitorum longus
42	Peroneus brevis	M. peroneus brevis
43	Infraspinatus muscle	M. infraspinatus
44	Rhomboid major muscle	M. rhomboidei major
45	Thoracolumbalis fascia	Fascia thoracolumbalis
46	Splenius capitis muscle	M. splenius capitis
47	Teres major muscle	M. teres major
48	Teres minor muscle	M. teres minor
49	Supraspinatus muscle	M. supraspinatus
50	Rhomboidei minor muscle	M. rhomboidei minor

Table 2 presents the types of movements and muscles involved in each movement (each muscle has its own number in accordance with table 1).

Table 2. Name of the muscles involved in different types of movement

Movement type	Muscles
1. Body tilt	7, 21, 23, 24, 25, 44, 45, 50
2. Arms bending	5, 9, 10, 11, 13, 15, 16, 17, 18
3. Straightening hands	5, 6, 8, 10, 12, 13, 14, 16
4. The leg curl	27, 28, 29, 30
5. Extension of legs	26, 29, 31, 32, 33
6. Flexion and extension of foot	37, 38, 39, 40, 41, 42
7. Rotation of the trunk	7, 19, 20, 21, 23, 24, 25, 43, 44, 47, 48, 49, 50
8. The rotation of the head and neck to the right and left	1, 2, 3, 4, 46

Table 3 presents the various training systems and the corresponding movement types (each type of movement has its own number in accordance with table 2).

Table 3. Simulators

Training systems	Movement types	The degree of automation of information acquisition
1. Exercise bike	4, 5	semi-automatic
2. Elliptical trainer	1, 2, 3, 4, 5, 6, 7	semi-automatic
3. Butterfly	3	mechanical
4. Pull vertical	1, 2	mechanical
5. Pull horizontal	1, 2	mechanical
6. Treadmill	4, 5, 6, 7	semi-automatic
7. CON-TREX	2, 3, 4, 5, 6	mechanical
8. Biodex System 3Pro	2, 3, 4, 5, 6	mechanical

The task and the technical result of this work are to increase an efficiency of diagnostics of pathology of individual muscles.

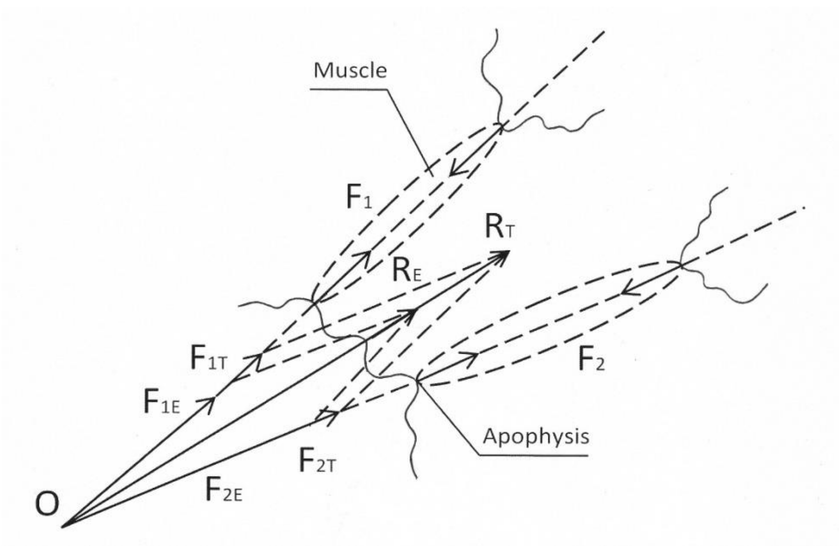

Figure 1. Graphical method of determination of the resultant muscles and its components

The task and the technical result are achieved by a method of evaluating the functional state of individual muscles of musculoskeletal system in the diagnosis and the preparation of athletes with a use of experimental and theoretical approach. The method consists of an experimental part for determination of the resultant muscle groupsR_E, involved in the execution of the selected movement for musculoskeletal system on the following automated training systems: "CON-TREX", "Biodex Multi-Joint System 3 Pro", or in their absence – conduction of the experiment with the sports weights; with the theoretical part aimed for the definition of a theoretically possible force produced by each muscle F_{iT}, according to the proposed formula by the authors, then by the rule of vector addition using the calculated F_{iT} and lines of action of these forces (figures 1 and 2) we define the theoretical resultantR_T. Some experimental resultant R_E we expand into components F_{1E} and F_{2E} (figure 1) by the rule of parallelogram, using lines of action of these forces according to X-rays (figure 2). In the case where the number of muscles in the group are more than two is used a sequential approximation. The resultant muscle forces F_{1E} and F_{2E} we compare in magnitude with the corresponding theoretical F_{1T} and F_{2T}, and if a difference for any muscle is more than 30%, we believe that it has a disease.

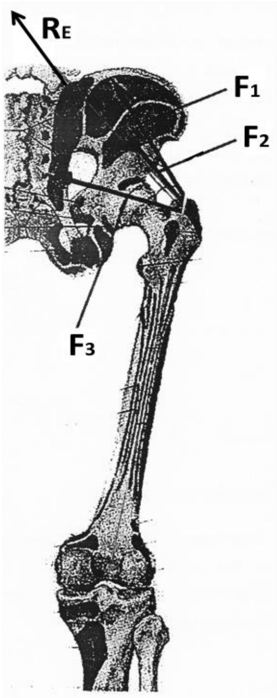

Figure 2. Radiographs of pelvis and hip

The implementation of the method is carried out in the following sequence:

1) define the scope of diseases (table 1);
2) choose the kind of movements of the musculoskeletal system according to the painful fillings (using table 1);
3) finding the group of muscles involved in the implementation of selected movements (using table 2);
4) choosing a fitness system that allows to implement the selected movement of the musculoskeletal system and determining the efforts realized by the muscle group (table 3);
5) we put the patient on the treadmill, gradually increasing the load, then we are recording results, for example, on the training system Biodex Multi-Joint System 3 Pro, we simulating cycling on the rise with the registration of the torque $M_{кi}$ in time t;
6) we repeat three times paragraph 5;
7) according to schedules we determine the maximum torque $M_к$, that a patient should be able to create;
8) the experimental resultant muscle groups of the lower extremities R_E involved in the execution of the selected movement, such as cycling, we define by the formulas:

$$M_к = R_{\mathbf{E}} \cdot h,\ R_{\mathbf{E}} = \frac{M_к}{h}, \qquad (1)$$

where h - is the distance from the axis of rotation of the pedals to the plane of the pedal;

9) to get the X-ray of the lower limbs (figure 2) on which to mark points on apophysis (mutual disposition of large bones corresponds to the position of a given movement);
10) on a separate sheet scale using X-ray (figure 2) to depict the contours of apophysis, to hold the dotted lines through the centers of apophysis (the lines of action of the forces resulted by muscles) till the intersection (figures 1 and 2);
11) on tomography to get the CT-scans of cross-sections (for the most area) of the muscles that participate in the execution of a given movement (figure 3);

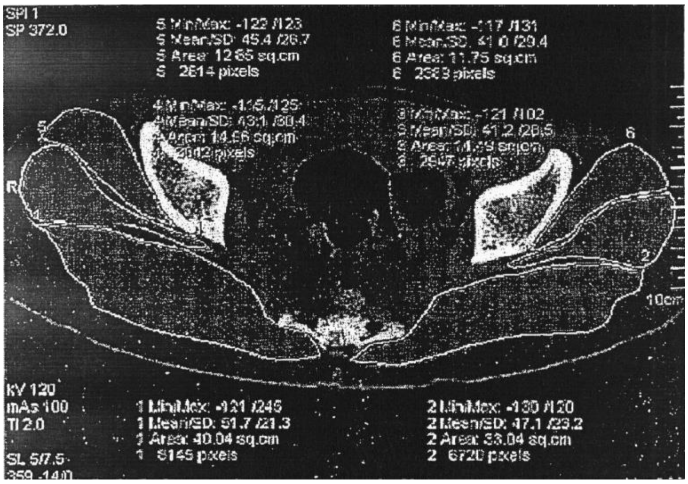

Figure 3. A CT-scan of the cross section of the muscles of the pelvis and hip

12) according to the proposed formula we determine the maximum developed force for each muscles:

$$F = \frac{S \cdot l \cdot c \cdot k_2 \cdot k_3 \cdot k_5}{L \cdot k_1 \cdot k_4}, \qquad (2)$$

where S is the area of the maximum cross-section of the muscle, determined by CT scan (figure 3), cm^2;
l - is the length of the muscle, defined as the distance between apophysises (figures 1 and 2), cm;
L - is the length of the muscle fibers with accounting the features of the arrangement of fibers in the muscle (parallel, pinnate, fusiform), the muscle structure (anatomy);
c - specific force of muscle defined by the maximum load that the muscle is able to raise per 1 cm^2 of its physiological cross section, it is determined by the table 4 [14];

Table 4. The specific strength of the muscles

The name of the muscle	c H/cm^2
Calf muscle	59
Flexor of the shoulder	81
The masseter	100
Biceps muscle of the arm	114
Arm triceps	168
The extensors of the neck	90
Smooth muscle	80

$k_1 \geq 1$ - coefficient taking into account the age of the patient, it is determined according to table 5;

Table 5. The influence of patient age on muscle state

Age, years	10	20	25	35	45	55	60	70	80	>81
Coefficient k_1	1,5	1,3	1	1,4	1,4	1,5	1,6	1,8	2,0	2,5

$k_2 \leq 1$ - coefficient depending on the angle of the fibers in the muscle to the axis of the tendon, is defined as the arithmetic mean of the three selected fibers according to table 6;

Table 6. The coefficients, taking into account the peculiarities of the muscles

The angle α, degrees	0	10	20	30	40	50	60	70
Coefficient k_2	1	0,9	0,8	0,7	0,6	0,5	0,4	0,3

The angle α is measured between the tangent to the axis of the muscle fiber and muscle (CT-scan in the longitudinal plane of the muscle.

k_3 - is a coefficient that is taking into account in which group the muscle is: slow - 1, fast - 0,7;
$k_4 \leq 1$ - is a coefficient that is taking into account patient's sex (male - 1, female - 0,65);
k_5 - is a coefficient that is taking into account a physical fitness; it depends on the type of professional work and sporting achievements, it is determined by the table 7 [15];

Table 7. Coefficients taking into account the physical condition of the muscles

Professional work	Mental work					Physical work				
Athletic performance	TRP	3 category	2 category	1 category	Master of sports	TRP	3 category	2 category	1 category	Master of sports
Coefficient k_5	0,8	1,3	1,5	1,7	1,90	1	1,4	1,6	1,8	2

13) theoretical forces F_{iT} are calculated according to the formula (2) in the scale, for example F_{1T} and F_{2T}**,** are deposited from point O (the intersection of the lines of action of the forces F_i), then according to the rule of the parallelogram is determined by the theoretical resultant R_T (figure 1) [16];
14) the experimental resultant R_E, is defined under paragraphs 6 and 7, and calculated by the formula (1), in a scale we measure from point O on the line of action of the resultant theoretical R_T (figure 1);
15) the experimental resultant R_E according to the rule of the parallelogram we spread out into components F_{1E} and F_{2E} according to forces F_1 и F_2 (figure 1);
16) we compared the experimental forces F_{1E} and F_{2E} with F_{1T} and F_{2T}, and if a muscle with the difference of more than 30% - it has the disease.

Example. The patient is a woman of 46 years old, height is 160 cm, weight is 65 kg, has an athletic performance - "Ready for labor and defense" (TRP), professional work - accountant, the symptoms: shosrtness of traffic on the stairs, pain in the region of the gluteal muscles, the cause of the disease - a fall on a slippery surface.

Let`s consider a diagnostic with sport weights in the absence of automated training systems.

The implementation of the method is carried out in the following sequence:

1) by palpation we define a pain in the region of the gluteal muscles;
2) providing the movement - lying on its side rises the lower limb;
3) the patient is laid on its side;
4) to the patient`s foot is attached the sling, in which is sequentially added weights of known weight;
5) is determined the maximum weight that the patient was able to raise by a leg, for the patient we got P_1;
6) we get a radiograph (figure 2) and CT-scan slice with the maximum cross-sectional area of the gluteal muscles (figure 3), according to them we found no damage of the bone tissue [17];
7) on the print of the radiograph (figure 2) we draw the vectors of the forces made by a group of muscles, which lines of action pass through the centres of apophysises, in this case we have F_1 **–** force of a gluteus maximus muscles, F_2 **–** force of gluteus medius muscle, F_3 - force of a small gluteal muscles;
8) on the CT scan (figure 3) based on the scope we defined the squares of the cross sections of the muscles, for this patient the results are shown in table 8 [18];

Table 8. Square of cross-sections of muscles

F_i	The main one-articular muscles involved in abduction of thigh	The cross-sectional area of muscle S_i (cm^2)
F_1	Gluteus maximus muscle	29,44
F_2	Gluteus medius muscle	9,58
F_3	Small gluteal muscle	4,01

9) by the formula (2) we define the theoretical maximum power F_{iT}, produced by every muscle of the patient;
10) to determine the strength F_{1T} from table 7, we have S = of 29.44 cm^2, from figure 4 (in a scale F_1) we have l = 4.5 cm, from table 4 (smooth) we have c = 80 H/cm^2, from table 7 (angle α = 10°) we have k_2= 0,9, for slow muscles k_3= 1, from table 5 we have k_5= 0,8, for side muscles we have L = 8 cm, from table 5 k_1= 1,4, in accordance with sex k_4= 0,65, then

$$F_{1T} = \frac{29{,}44 \cdot 4{,}5 \cdot 8 \cdot 0{,}9 \cdot 1 \cdot 0{,}8}{8 \cdot 1{,}4 \cdot 0{,}65} = 2096 \text{ H};$$

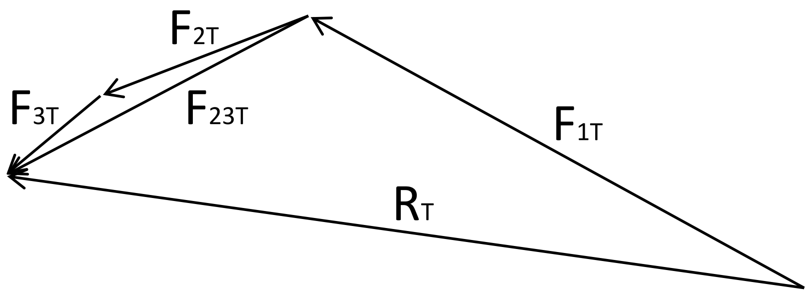

Figure 4. Graphical definition of the resulting experimental muscle

11) to determine the force F_{2T} from table 8 we have S`= 9,58 cm^2, from figure 4 (in a scale F_2**)** we have l = 2.5 cm, from table 4 (smooth) we have C = 80 H/cm^2, from table 6 (angle α = 10°) we have k_2 = 0,9, for slow muscles k_3= 1, from table 7 we have k_5= 0,8, for side muscles on figure 3 we have L = 2 cm, from table 5 k_1= 1,4, in accordance with the floork_4= 0,65, then

$$F_{2T} = \frac{9{,}58 \cdot 2{,}5 \cdot 8 \cdot 0{,}9 \cdot 1 \cdot 0{,}8}{2 \cdot 1{,}4 \cdot 0{,}65} = 936 \text{ H};$$

12) to determine the force F_{3T} from table 8 we have S`= 4,01 cm^2, from figure 4 (in a scale F_3) we have l = 4 cm, from table 4 (smooth) we have c = 80 H/cm^2, from table 6 (angle α = 10°) we have k_2= 0,9, for slow muscles k_3= 1, from table 7 we have k_5= 0,8, for side muscles according to the figure 3 we have L = 3.5 cm, from table 5 k_1= 1,4, in accordance with sex k_4= 0,65, then

$$F_{3T} = \frac{4{,}01 \cdot 4 \cdot 8 \cdot 0{,}9 \cdot 1 \cdot 0{,}8}{3{,}5 \cdot 1{,}4 \cdot 0{,}65} = 290{,}4 \text{ H};$$

13) we determine the theoretical resulting force R_T by method of a vector addition of vectors F_{1T}, F_{2T}, F_{3T} (figure 4), from figure 4 we get R_T = 318 kg = 3180 H;
14) to determine the experimental resultant force R_E we make the design scheme with the use of the anthropometric characteristics of the patient: OC = 66 cm - distance from the center of the head of the hip joint to the point of suspension of the load (point C); OK = 50,7 cm - distance from the center of the head of the hip joint to the center of gravity of the leg (the coordinates of the center of the whole feet) [19]; α = 27°C, - the maximum deflection of angle of the legs of the patient from the horizontal (figure 2), where is presented the deviation with load without a significant pain; h = 2.6 cm- distance from the center of the head of the hip joint to the line of action R_E (the lines of action of forces R_E and R_T in parallel), as determined by X-ray; P = 65 · 0,2 = 13 kg = 130 H - the weight of the foot, which is 20% of the total weight of the person [20]; P_1 = 1,2 kg = 12 H – the maximum load that could raise a patient;
15) we determine the resultant experimental R_E from the moment condition of the equilibrium of feet with the load (figure 1), instantaneous point - the centre of the hip joint:

$$R_E = \frac{P_1 \cdot OD + P \cdot OV}{h} = \frac{1{,}2 \cdot 58{,}7 + 13 \cdot 45{,}1}{2{,}6} = 205{,}2 \text{ kg} = 2052 \text{ H},$$

OD = OC · cosα = 66 · cos27° = 58,7 cm,
OV = OK · cosα = 50,7 · cos27° = 45,1 cm;
16) let`s determine the resultant F_{2T} and F_{3T}, $F_{23T} = F_{2T} + F_{3T}$; by the method of triangle (figure 4),
(17) the vector R_T we move to the center O (figure 1), on the line of action of the vectorR_T from the point we begin the resultant experimental R_E= 2052 H according to item 15, according to the rule of the parallelogram (figure 1) we decompose the resultant R_E into components F_{1E} and F_{23E} along the lines of the action, then the vector F_{23E} is decomposing on components F_{2E} and F_{3E} we get F_{1E} = 1505 H, F_{2E} = 936 H, F_{3E} = 274 H;
18) then we determine the percentage deviation of the forces produced by the muscles, that were found experimentally, theoretically:
for the force F_1- 39%,
for the force F_2- 71%,
for the force F_3- 6%;
19) the conclusion - the most injured were the medium and large gluteal muscles, the small gluteal muscle did not require treatment.
In the absence of a training system with the necessary registration of experimental data we show a variant of modernization on the example of the exercise bike. Figure 5 is a functional block diagram of the system.

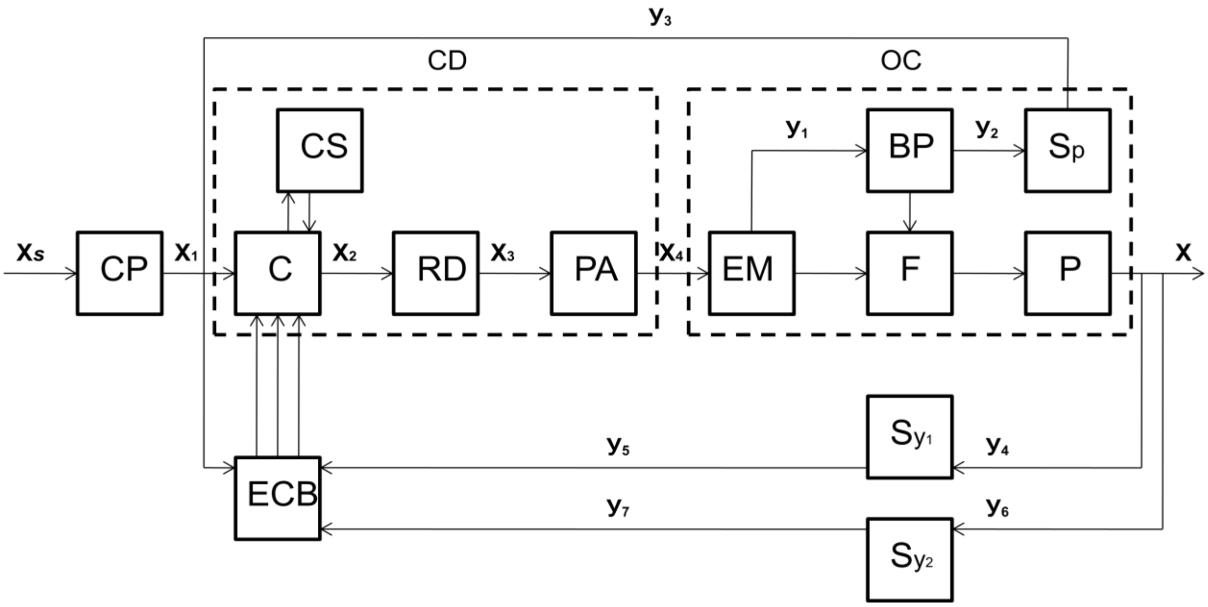

Figure 5. Functional diagram of the control system to upgrade the exercise bike

Figure 5 shows a functional structure of the control system (CS) with elements: CP – control panel, CD – control device, OC – the object of control, C – computer, CS software, RD – regulating device, PA – power amplifier, EM – electromagnet, F – flywheel exercise bike, BP – brake pads, P – patient, S_y – sensors receiving a signal from the patient (heart rate and blood pressure), S_p – pressure sensor, ECB – electronic control unit.

This control system is a closed loop system. Control system with closed loop is always covered by the feedback loop [21, 22]. Drive signal x_s arrives to a system controller CP. Further, the signal x_1 (set parameters) from the control panel goes to the computer C. Then the computer sends a signal x_2 to a regulating device RD, which sets the desired load level. Next, from the control device arrives a signal x_3 to the power amplifier which gradually increases the load in accordance with a predetermined program. From the amplifier the signal x_4 goes to the electromagnet EM, which transmits a control mechanical effect on the brake pads BP. Then the electromagnet activated by a signal y_1 gradually presses the brake pads to the flywheel F. The pressure sensor S_p is installed on the brake pads, it measures the pressure (by means of a signal y_2), with its help the electromagnet pushes the brake pads to the flywheel, and by a signal y_3 it transmits the received information to the computer via the electronic control unit ECB.

On the patient P are installed sensors S_{y1} and S_{y2}, which receive signals from the patient (his pulse and blood pressure). Through signals y_4 and y_6 these sensors record information about the patient's condition and using signals y_5 and y_7 enters the computer via an electronic control unit. For example, if during the diagnostic conditions occur the deviation of patient`s heart rate and blood pressure from the norm, then these two sensors will immediately report this information to the computer which will immediately switch off the system.

CONCLUSION

The result of this work is the ability to diagnose each muscle of the musculoskeletal system using automated and semi-automated training systems, and common mechanical systems. We have proposed a variant of modernization of the mechanical system, which will simplify diagnostics and rehabilitation for diseases of the musculoskeletal apparatus. In addition, this technique can be used by sport-trainers to prepare elite athletes. We are developing software tools for complete automation of the study of the muscular system and proposals to replace part of a mechanical device for the existing training systems. For example, the replacement of loads system by the disc with the brake pads. The controlled brake pads will create the effect of lifting. There could be a variant of the motor with the loading resistance and electric batteries. In this case, the system will become completely energy-autonomous.

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