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TECHNOLOGIES FOR MEASURING THE DYNAMIC PARAMETERS OF ROWING BASED ON STRAIN GAUGE SYSTEMS

D.I. Guseinov[1], T.V. Permyakov[2], A.L. Narkevich[3], D.A. Lukashevich[4], A.V. Minchenya[5]

[1] Belarusian State University of Physical Culture, Minsk, Republic of Belarus
[2] Belarusian National Technical University, Minsk, Republic of Belarus
[3] Belarusian State Technological University, Minsk, Republic of Belarus
[4] Scientific and Technological Park of BNTU "Polytechnic", Minsk, Republic of Belarus
[5] LLC "Integrated Devices", Minsk, Republic of Belarus

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ABSTRACT

One of the criteria for the effectiveness of flatwater rowing biomechanics is the interaction of the athlete with the surface of the water by an oar, as well as the effectiveness of transferring the efforts developed by the athlete to the boat for its advancement. The quality of an athlete's movements with a paddle in rowing locomotives depends on the level of development of power abilities and can be quantified using strain gauge systems. However, the lack of recommendations describing the specifics of the preparation and use of such systems in training process significantly reduce the degree of their use. The article discusses the technical features and methodological foundations of the use of strain gauge systems to measure the efforts of an athlete when interacting with an oar in flatwater kayaking and canoeing. To substantiate the choice of the scheme of loading and securing the paddle when graduating the strain gauge system, as well as the place of its direct attachment to the forearm, the authors carried out mathematical modeling of diagrams of bending moments arising on the paddle in response to external forces, as a result of which three options for the support and orientation of the paddle are presented, depending on the location of key support points. To substantiate the method of attaching the strain gauge system to the forearm, a series of tests with paddle loading was carried out, as a result of which the presence of a linear relationship between the values of the external load and the readings of the strain gauge system was assessed, as well as the repeatability of the recorded data. Based on the results of the assessment, recommendations are presented for the practical application of the results of the study in assessing the speed and strength training of rowers on kayaks and canoes.

Introduction

It is difficult to imagine the training process today without a variety of measuring systems, with the help of which coaches receive quantitative information about the motor actions of athletes. The main criteria for the pedagogical value of such systems are the informativeness and efficiency of the information received, ease of registration, processing and comparative analysis of data on key parameters for different athletes or for different training sessions of one athlete [6, 9, 13, 14].

It is known that the rationality of an athlete's interaction with an oar in flatwater rowing and canoeing is one of the key factors of athletic performance [1, 2, 15]. This is due to the fact that the effectiveness of boat promotion depends on the physical condition and the level of coordination of the athlete's movements, ensuring maximum transformation of the effort of each stroke into acceleration of the boat [5, 8, 18].

© **Daniil I. Guseinov** – Engineer, e-mail: guseynov.daniil@yandex.by iD 0000-0003-4812-1832
© **Trofim V. Permyakov** – Ph.D. Student
© **Anna L. Narkevich** – Ph.D., Associate Professor, e-mail: v-krivka@mail.ru iD 0009-0006-1775-3027
© **Dmitrij A. Luckashevich** – Ph.D., Associate Professor, e-mail: dmitry.luckashewi4@yandex.by iD 0000-0003-3506-9430
© **Aleksandr V. Minchenya** – Director, e-mail: alex_minch@mail.ru

For these reasons, studying the process of transferring an athlete's effort to the oar will increase the objectivity of assessing the level of technical and speed-strength training of athletes in rowing locomotives [3, 4].

To solve this problem, a promising direction is the use of measuring systems implemented on the basis of resistive elements to assess the dynamic parameters of athletes' movements [1]. At the same time, the objectivity of information obtained using such systems is largely determined by the quality of their calibration, the place of attachment and other factors that may affect the accuracy of the data obtained [10, 16]. The first data on the use of wired strain gauge systems in flatwater rowing and canoeing appeared in the late 80s of the last century [17]. However, the systems used at that time were quite cumbersome, the analysis of the array of data obtained was time-consuming and time-consuming, which limited the possibility of introducing such tools into the wide practice of training athletes.

According to a number of researchers, a measuring system mounted on the rowlock of an academic rowing paddle, operating on the basis of a strain gauge (hereinafter referred to as a strain gauge), allows you to accurately and quickly obtain information about the load values during rowing, which in turn allows you to analyze its effectiveness [12]. The same authors summarize that the installation of a load cell does not require complex manipulations, its presence does not significantly affect the biomechanical structure of an athlete's movements, and its practical significance is due to the possibility of obtaining accurate data that is used to adjust rowing techniques and improve athletic performance.

In the works [7, 10, 11], the rationale for the use of a wireless measuring system based on a strain-resistant sensor mounted directly on the paddle in a flatwater rowing and canoeing is given, its design and software features are described, and the results of testing the measuring system in natural training conditions are presented. However, in order to increase the reliability of the results obtained, it is necessary to have a theoretical and experimental justification for the choice of paddle loading schemes, the attachment point of the load cell on the paddle and the justification of the methodology for carrying out the calibration of the paddle, in order to obtain the most accurate information in real conditions of rowing locomotions. This is due to the fact that unlike academic rowing, where the force generated by the oar is transmitted to the athlete's body through the oarlock and there is a fixed anchor point for calculating the interaction forces, in uncluttered rowing, the force applied to the oar during movement is transmitted to the athlete's body through the support surface of the boat and the cushion under the knee and it depends largely on the athlete himself [19].

The purpose and objectives of the study

The purpose of this work is a theoretical and experimental substantiation of the use of strain gauges for measuring an athlete's efforts when interacting with an oar in flatwater kayaking and canoeing.

To achieve this goal, the following objectives are formulated:

– selection and justification of the scheme of loading and securing the paddle during calibration of the load cell;

– the choice of the attachment point of the sensor on the paddle, which will not create discomfort for the athlete, but at the same time will ensure the greatest sensitivity of the measuring system;

– the choice of a method of mounting the load cell on the paddle, which minimizes the possible distortion of the recorded data and will allow them to obtain linear dependences on the external load;

– evaluation and analysis of the linearity and repeatability of the recorded data;

– experimental determination of the conversion coefficient of the measuring system during calibration of the load cell;

– development of recommendations for the calibration of the measuring system, regardless of the model of the paddle.

The object and subject of the study

The object of the study is a paddle for canoeing with a pre-installed load cell. The subject of the study is the place, method of attachment and calibration characteristic connecting the output signal of the load cell and the force on the paddle blade.

For the research, a carbon fiber composite paddle model was selected that meets the requirements of international competitions. As a priori, it is known that in working condition, the individual parts of the paddle are always stationary relative to each other, while the paddle is conditionally divided into three parts: the blade, the rod (shaft, forearm) and the handle. The paddle blade perceives the water resistance during the stroke – this was taken into account by us when choosing loading equipment when performing calibration work. There was a technological bias along the entire length of the rod of the oar under study, which was taken into account when choosing the method and mounting elements of the load cell, the T-shaped handle had the ability to rotate and lock around the axis of the oar rod for individual adjustment, while one of the supports during calibration of the load cell was located in the experiment under the central point of the handle.

The load cell, as a design, was a metal beam with glued strain gages and enclosed in a protective housing. In working condition, the metal beam was adjacent to the surface of the paddle rod. The strain gauge was glued on the side of the beam opposite to the surface of the paddle rod, and the axis of the strain gauge coincided with the axis of the paddle rod. Thus, the beam, repeating the elastic bending line of the paddle forming the rod, eliminated the need to stick expensive strain gages directly on the rod and acted as an extensometer.

The work in this study was carried out using the material and technical base of the Department of Mechanics and Engineering of the educational institution «Belarusian State Technological University».

Research methods and the results and their discussion

When choosing the paddle loading scheme for the calibration of the load cell, we were guided by the scheme of loading the paddle under operating conditions (during rowing), as shown in Fig. 1 [4] (here and further, the inclined dotted line in the area of the paddle blade demonstrates the orientation of the paddle relative to the applied forces).

During rowing, the athlete, applying F_{TL} and F_T forces, must overcome the resistance of the aquatic environment, accepted as the resultant reaction R_C from the load distributed on the paddle (not shown here). As a result of these actions, the boat will move in the direction of the vector of the resulting acceleration of the system a (Fig. 1), opposite to the action of the reaction medium R_{C1} – the horizontal component of the resultant R_C. Due to the fact that the forces applied to the oar in the working phase of the rowing cycle are several tens of times higher than the weight of the oar, in the loading schemes discussed below, the oar's own weight is neglected.

The listed forces or their components (indicated by F_i for convenience), directed perpendicular to the axis of the paddle rod (Fig. 2, *a*), lead to bending of the rod. The location of point A corresponds to the location of the grip of the pushing arm, point B corresponds to the pulling arm of the rower; section CE corresponds to the area of the paddle blade. According to the diagram of bending moments (Fig. 2, *b*), it can be seen that the greatest bending moment will be at point B.

It should be noted that the distributed load $q(z)$, N/m, on the CE section at any moment of the stroke cycle has a non-constant value along the z axis and can be obtained by multiplying the high-speed water pressure, Pa, by the value of the width of the paddle blade, m, at each point along the length L_3+L_4. Also, the distribution of $q(z)$ will depend on the depth

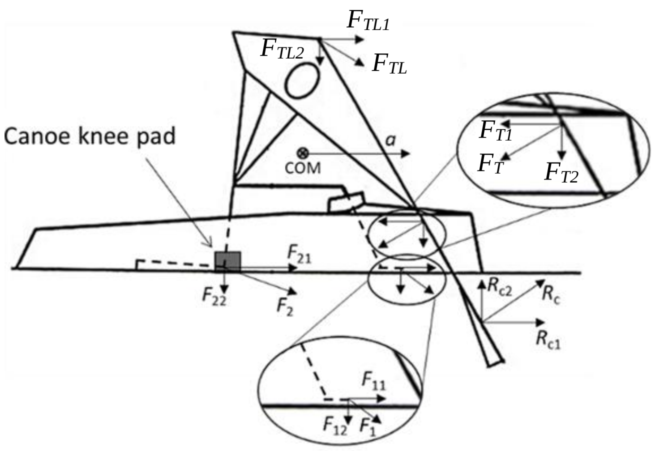


Fig. 1. Diagram of the acting forces on the paddle in the «athlete – paddle – aquatic environment» system [4]: F_{TLi} – forces created by the pushing arm of the athlete; F_{Ti} – forces created by the pulling arm of the athlete; R_{Ci} – reactions of resistance of the aquatic environment; F_i – forces applied by the athlete to the support surface of the boat (F_1) and a knee cushion (F_2) for propulsive action to propel the boat

of immersion of the blade and on its shape in the *xz* plane. However, the nature of the distribution $q(z)$ does not affect the values of bending moments in the sections of the rod AB and BC in any way, and only the value of the resultant force F_3 (shown in dotted line) and the point of its application D (the section of the bending moments plot built on the section CD for the concentrated force F_3 is shown in dotted line) will have an impact. Expressions for bending moments on the AC segment will be written as:

$$M^x_{\max} = F_1 \cdot L_1, \tag{1}$$

$$M^x_{AB}(z) = F_1 \cdot z, \tag{2}$$

$$M^x_{BC}(z) = F_1 \cdot L_1 - F_2 \cdot (z - L_1). \tag{3}$$

The same ratios can be used if the calibration was performed, for example, under the force F_3, and after the training process it is necessary to perform an analysis of the force, for example, F_1.

Due to the fact that the shapes of the paddle blades of different models differ, as well as due to the different depth of immersion of the paddle in the working phase of the rowing cycle, as mentioned above, we assume for certainty when graduating the load cell (and later – to evaluate the athlete's work) that the force F_3 is concentrated on half the length of the paddle blade, i.e. $L_3 = L_4$.

To implement the loading scheme during the calibration of the load cell, three support schemes are possible, shown in Fig. 3, in which, in turn, pivotally movable and pivotally fixed supports can be interchanged. The paddle in each of the loading schemes should be oriented in such a way that the stretching and compression zones on the paddle rod correspond to the operating conditions.

The choice of the support scheme does not affect the measurement results and will depend only on the technical capabilities of the equipment of the measuring stand or equipment, which significantly expands the possibilities for calibration of any paddle models in the conditions of the training base.

In order to carry out the correct calibration, it is necessary to load the entire range of possible forces that are applied to the paddle during operation. The initial data on the forces can be the value of any of the forces – F_1, F_2 or F_3, regardless of which of the support schemes is selected. And the active force that will be applied to the paddle, during calibration according to a known force and size, can be calculated by expressing it from the following equations of sums of moments relative to points on the paddle (Fig. 3):

$$\sum M_A = 0:\ F_2 \cdot L_1 - F_3 \cdot (L_1 + L_2 + L_3) = 0, \tag{4}$$

$$\sum M_B = 0:\ F_1 \cdot L_1 - F_3 \cdot (L_2 + L_3) = 0, \tag{5}$$

$$\sum M_D = 0:\ F_1 \cdot (L_1 + L_2 + L_3) - F_2 \cdot (L_2 + L_3) = 0. \tag{6}$$

The lengths (dimensions L_i) are individual for each model of the paddle, and also depend on the anthropometry of the athlete who chooses the place of grip (point B, Fig. 3) on the rod of the paddle. The individual location of point B is defined as the point between the middle and ring fingers of the pulling hand when it covers the paddle rod in operating mode.

The location of the load cell on the paddle rod is influenced by several factors.

It is preferable that the strain gauge experiences tensile deformations during operation, therefore, on the bent rod of the paddle, the load cell must be positioned above the part of the forearm that will experience tension under operating conditions, as shown in Fig. 3. The section of the paddle rod with a fixed load cell is shown in Fig. 4.

The position of the *x*-axis is naturally defined as a straight line parallel to the plane of the paddle blade passing through point D (Figs. 2 and 3).

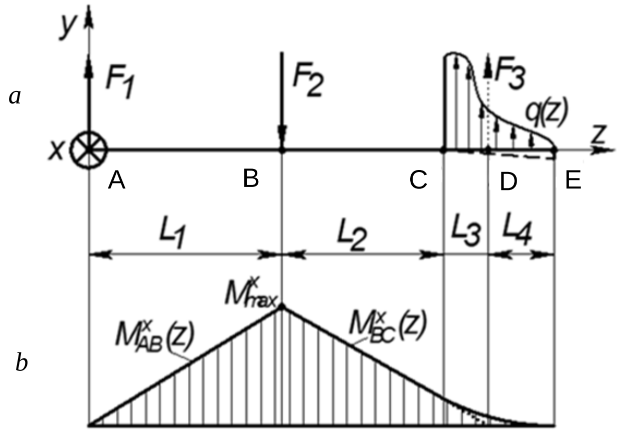


Fig. 2. The scheme of loading the paddle under operating conditions with forces perpendicular to the axis of the rod (*a*) and the corresponding diagram of bending moments (*b*)

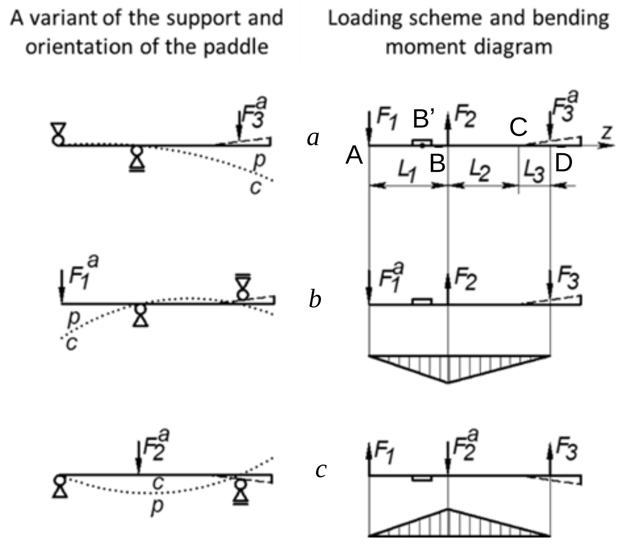


Fig. 3. Options for the support and orientation of the paddle for the implementation of loading schemes during calibration of the load cell: dotted line – the deformed state of the paddle; *a* – for active force; *b* – stretching; *c* – compression

Due to the relatively rigid design of the paddle rod, as well as taking into account the permissible deformations for the strain gauge, it is advisable to place the load cell in the area with the greatest possible deformations of the paddle. It is known that during bending, linear deformations of the longitudinal layers of the paddle rod, to which the load cell actually reacts by changing the output signal, are directly proportional to the bending moment and have the greatest values on the surface of the rod at the point furthest from the neutral line (Fig. 4):

$$\varepsilon_{max}(z) \propto M^{x}(z) \cdot y_{max}. \qquad (7)$$

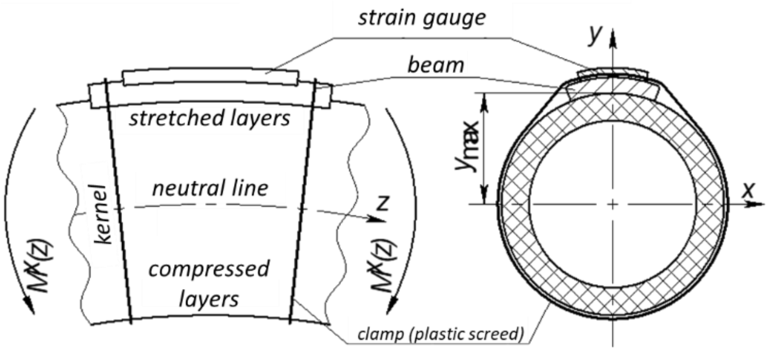
However, it is not possible to place the load cell directly at the point B of the maximum bending moment $M^{x}_{\max}$, since at this point the forearm is covered by the athlete's hand. Therefore, the location of the load cell enclosed in the body (point B' in Fig. 3 is the center of the sensor strain gauge) in the axial direction should be shifted from point B towards point A (preferably) or to point C by the minimum allowable distance, which will not cause discomfort to the athlete when controlling the paddle during rowing. The distance from point B to the end face of the sensor housing can be about 10–15 cm.

For further research, the loading scheme shown in Fig. 3 was selected, and. To create a load F_3^a at point D, the universal electronic testing machine MTS Criterion 43 was used (the limits of the permissible relative error of force measurements are no more than 1 %), which allows loading at a constant speed and in a given load range. A tube with a radius of 8 mm was used as an indenter, horizontally fixed in the upper grip, with a length exceeding the width of the paddle blade at point D (Fig. 5).

To support the paddle at points A and B, a rigid frame structure is assembled as an extension of the platform of the test machine: at point A, a pivotally non-movable support is implemented, and at point B, a pivotally movable support (Fig. 6) with rounding radii of 10 mm.

When loading the paddle to move the traverse of the test machine, it is necessary to set the loading speed, and not the speed of movement of the traverse (in studies, the loading speed $\dot{F}$ = 160 N/min = 2.667 N/s is accepted), in order to exclude the possible nonlinearity of the dependence of the load on the traverse movement at the initial deformation site, which in turn may distort the evaluation of the output signal data load cell. Thus, the dependence of the load F_3^a on the t_F time during loading has a linear dependence, the correlation coefficient for which, according to the results of idle (without the use of a load cell) loads, was 1.0.

When choosing the method of attaching the load cell to the paddle rod, it must be taken into account that when bending the rod, in addition to linear longitudinal deformations, the cross-sectional layers also shift relative to each other parallel to the neutral line. Moreover, such shifts will occur at the junction of the paddle rod and the load cell beam.



a *b*

Fig. 4. *a* – deformed state of the paddle rod and load cell under the action of the bending moment $M^x(z)$ (*a*); *b* – the cross section of the rod at the installation site of the load cell

Fig. 5. Paddle blade and indenter for applying load F_3^a at point D, fixed in the grip of the MTS Criterion 43 test machine

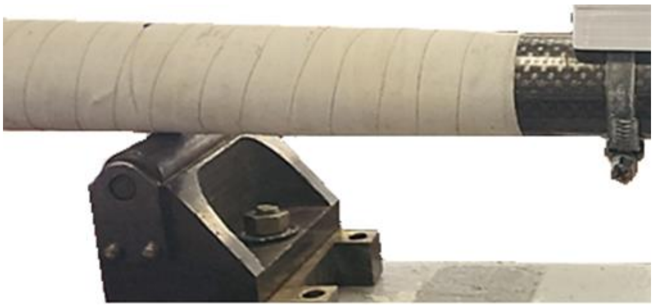


Fig. 6. The rod of the paddle on the hinge support at point B

To minimize shifts during bending of the paddle rod and to obtain the greatest sensitivity of the load cell, the load cell beam should be as close as possible to the surface of the paddle rod and be rigidly fixed to it. After the termination of the loads that caused the bending of the paddle rod, the load cell beam must return to its original state. But at the same time, the fasteners used and the surface of the load cell beam should not lead to damage to the surface layer of the paddle rod both when installed on the paddle and when it is cyclically loaded during rowing. Nevertheless, the shift of the load cell beam relative to the surface of the paddle rod is also allowed, but the strain gauge deformations in this case will be lower than in the above case.

In any case, the presence of a load cell on the paddle section should not distort its elastic line, and additional deformations that are not characteristic of bending should not appear in the load cell beam.

The beam of the load cell used in the research, as shown in Fig. 4, had a curved cross section that practically repeated the outer contour of the paddle rod, and clamps and ties were used to attach the load cell beam to the paddle rod.

We tested three methods of fastening the load cell, the description of which is given in Table 1. Metal clamps provide the greatest adhesion between the beam and the rod, therefore, this type of fastening for schemes 1 and 2 was adopted as a rigid seal. The antifriction layer (in the experiment, double-sided siliconized paper) in combination with more pliable plastic ties made it possible to realize the longitudinal sliding of the beam in schemes 2 and 3 relative to the rod when it is bent. For a tighter fit of the load cell to the rod, but at the same time to maintain mobility, a pair of narrow ties for one mount was used.

Loading in all tests was carried out to the most characteristic value of the maximum load on the paddle blade $F^a_{3\ \max} = 320\,N$. During loading, records were made in separate data arrays of load cell readings with a frequency of 270 Hz (to the memory card of the recording system) and external load readings with a frequency of 10 Hz (to a temporary test data recording file); records began and ended synchronously. Then, using the obtained data arrays, dependencies were built for the readings of the output signal of the load cell U on the time t_U and for the load values F_3^a on the time t_F (Fig. 7).

Since the graphs of the dependence of the load F_3^a on the t_F time were linear dependencies also with a correlation coefficient of 1.0, this allowed the graph of the dependence U on t_U to be «translated» into the calibration characteristic U from F_3^a (the output signal of the load cell from the external load), multiplying each value of the time at which the output signal of the load cell was recorded by the loading rate $\dot{F}$:

$$F_3^a = t_U \cdot \dot{F}. \quad (8)$$

For each fastening method, five tests were performed, and before each test, the load cell was removed and installed again according to the marks, simulating the real conditions of use of the load cell, when after mounting the sensor on the paddle rod and conducting the calibration procedure, it can be dismantled until the load cell is directly used in the training process.

The results of plotting for all fastening methods are shown in Fig. 8 in one coordinate system; in view of the overlap of the graphs of individual tests for the 2-nd and 3-rd fastening methods (Table 1), they are shown in one graph.

Observations and conclusions based on the results of tests on the 1-st method of fixation are as follows. In the first experiment (no. 1 in Fig. 8) we obtained a dependence conditionally consisting of three sections: a short initial linear, a transitional nonlinear and the longest linear. That is, the initial «rigid» behavior of the load cell was observed, when significant changes in the output signal corresponded to minor changes in the load, and the final «malleable» behavior of the load cell, when large changes in load values corresponded to the same changes in the output signal. Having associated this behavior with insufficient tightening of the clamp and shifts of the beam surface relative to the surface of the paddle rod, a gradual increase in the tightening torque was performed (from test no. 2 to test no. 5, Fig. 8), which naturally led to an expansion of the «rigid» behavior of the load cell to about 10 N, but after passing the transition section, starting with a load of about 100 N, the «malleable» behavior of the sensor was repeated: the dependence graphs on the final linear sections for samples from no. 1 to no. 5 are almost parallel. Further increase of the torque will inevitably lead to damage to the surface of the paddle rod. It should be noted that at low load values, as well as when it is possible to rigidly fix the load cell on the surface of the inventory, the 1st method of fastening will be useful, but will not be acceptable for paddles in non-emergency rowing. However, the ability of the metal clamp to securely hold the load cell beam in a fixed position was used to test the 2-nd fastening method.

When using the 2-nd and 3-rd methods of fixing the load cell by using pairs of couplers, the surface of the load cell beam was tightly fitted to the surface of the paddle rod, and the use of an antifriction layer facilitated an unhindered shift of the mating surfaces relative to each other during bending of the rod: for the 2-nd method of fastening – on the one hand, for the 3-rd method the fixings are on both sides. For both cases, linear dependencies were obtained over the entire load range (Fig. 8).

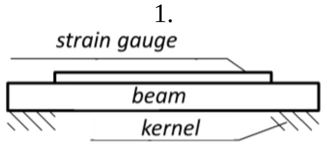
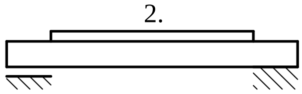
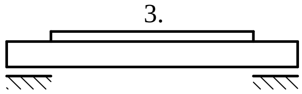
To objectively assess the presence of a linear relationship between the values of the external load and the strain gauge readings, the correlation coefficient and the approximation coefficient obtained during data processing in Excel were used (Table 2).

The values presented in Table 2 show that both cases of the data obtained are characterized by a high degree of correspondence of the model of linear dependence between the external load on the paddle blade and the values of the output signal of the load cell fixed in the central part of the paddle rod. The value of the approximation coefficient close to 1.0 indicates the presence of a functional linear dependence, which is fully explained by the physical nature of the working part of the strain gauge and the linear relationship between deformation and external bending force for the paddle material.

To assess the repeatability of the data recorded by the strain gauge system in each test group (for the 2-nd and 3-rd methods) in the laboratory, we will use the calculation and analysis of the following parameters: the coefficient of variation of the slope angle tangent for linear dependence (Fig. 8) and the Euclidean metric.

Table 1

Methods of mounting the load cell on the paddle rod

Method number and fastening scheme	**An illustration of the implemented method**
1.  Metal clamp Metal clamp	
2.  Plastic screed and antifriction layer; Metal clamp	
3.  Plastic screed and antifriction layer; Plastic screed and antifriction layer	

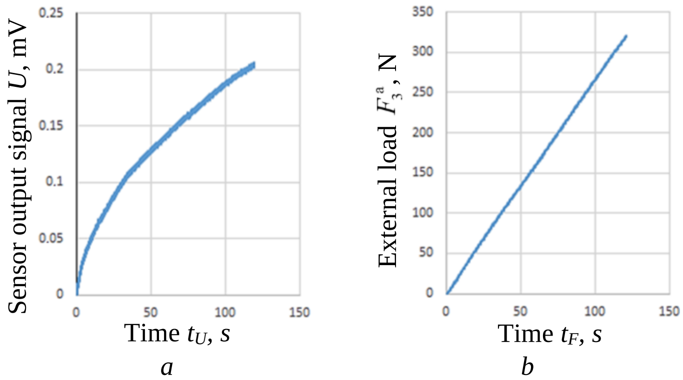


Fig. 7. Dependences of load cell readings U on time t_U (*a*) and load F_3^a on time t_F (*b*) on the example of test no. 1 for the 1-st fastening method

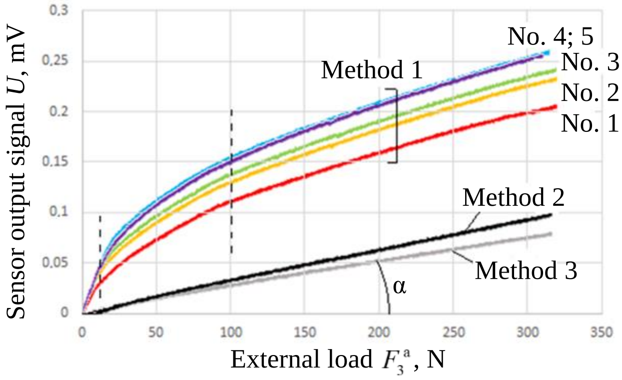


Fig. 8. Dependence of the load cell output signal on the applied external load F_3^a; the dotted line conditionally shows the boundaries of the sections

The calculation of the Euclidean metric for two arrays of load cell readings p_k and q_k according to a well-known formula allows you to obtain absolute values:

$$d(p,q) = \sqrt{\sum_{k=1}^{n}(p_k - q_k)^2}. \quad (9)$$

Analyzing the relative values of the Euclidean metric for the measuring system, it can be concluded that the repeatability of the data recorded by the system for the 2-nd and 3-rd fixation methods can be characterized as high.

Note that the 3-rd type of fastening, due to the freedom of displacement in the longitudinal direction on both sides due to the taper of the rod, as well as the absence of an obstacle to rotation in the circumferential direction due to the cylindrical outer surface of the rod, will eventually affect the stability and correctness of the load cell data, i.e. for measurements in this design, the 3-rd method of fixing the load cell is not suitable. And fastening the load cell beam with a metal clamp on only one side prevents relative displacement in both the longitudinal and circumferential directions, securely fixing one end of the load cell beam. Moreover, it is advisable to install a metal clamp at the end of the load cell beam, which is located above the area with a large diameter of the paddle rod to maintain a tight fit of the sensor beam to the paddle rod.

So, the most acceptable method of fastening is reasonably the 2-nd method (Table 1), which minimizes the possible distortion of the recorded data, allows you to obtain their linear dependences on the external load with good repeatability of the data associated with the external force on the paddle.

To process the load cell data, of course, a conversion factor of the measuring system is required, which will convert the data of the load cell output signal in mV into force values in N.

The tangent of the slope angle α for the linear dependence graphs in Fig. 8, constructed according to the above described method, can actually be considered the conversion coefficient k_U, measured in units of mV/N, its value can be easily obtained after constructing a regression line, for example, in Excel. But for practical use, it is more convenient to use the inverse value in units of N/mV:

$$k_F = 1/k_U. \quad (10)$$

For example, according to the test results for the 2-nd method of fastening for a certain model of an oar with a given athlete's grip point in the central part of the oar rod, the value $k_U = 0.2363 \cdot 10^{-3}$ mV/N was obtained, then according to the formula (6) $k_F = 4232$ N/mV.

The values of the load cell output signal are multiplied by the resulting coefficient, obtaining the required forces on the paddle during rowing over time.

Due to the obvious differences in the data in individual samples (2-nd and 3-rd methods), for a more objective assessment, we apply the ratio of the Euclidean metric to the largest value in the p_k and q_k data arrays. The calculation results are presented in Table 4.

Recommendations for the practical application of the research results in the assessment of speed and strength training of rowers

The conversion factor for each model and size of the paddle, as well as when using the paddle by a particular athlete, will have an individual value. The load cell in the laboratory, at the request of a sports organization, can be calibrated using an automated loading system of the test machine for almost any paddle and taking into account the individual data of the athlete.

But for a wide application of the measuring system, it is advisable to calibrate the strain gauge directly in the conditions of the training base.

The most acceptable option for supporting the oar in the conditions of a training base is to use the scheme (Fig. 3, *c*), when both supports are under the oar. Further recommendations are provided for this scheme.

In any case, before installing the paddle on the supports,

Table 2

Numerical estimation of linear dependencies (coefficients of variation in parentheses, %)

Mounting method	The average value of the correlation coefficient	The average value of the approximation coefficient
2	0.9991 (0.007)	0.9982 (0.018)
3	0.9924 (1.047)	0.9849 (2.247)

Table 3

Statistical characteristics for the slope angle tangent α linear dependence

Mounting method	Average value, mV/N	Coefficient of variation, %
2	$0.2363 \cdot 10^{-3}$	1.14
3	$0.2986 \cdot 10^{-3}$	1.67

determine the position of point B (Fig. 3) by the location of the athlete's grip, as described above – a load will be applied at this point. Then, retreating 10–15 cm from point B, preferably towards point A, mark the boundary of the load cell body, for example, with adhesive tape along the perimeter of the circumference of the cross-section of the paddle rod. Based on this marking, mark the position of the center of the load cell in the axial direction and fix it in the 2-nd way (Table 1) loosely so that it can be rotated when adjusting the position in the circumferential direction.

Due to the complex geometry of the handle, it is permissible to rest at point A (Fig. 3) at the junction of the rod and the handle, since the distance from the center of the handle to the junction is small compared to the length of the paddle rod.

Then mark the position of point D (Fig. 3) in the middle of the length of the paddle blade. After placing the paddle blade on the horizontal supports, in particular at point D, the orientation of the load cell in the circumferential direction will naturally be determined, which will finally fix the load cell in the working position (in the selected scheme, the sensor will be located in the lower part of the paddle – see Fig. 3). Here it is also important to perform an indelible marking of the sensor position (or its buildings) during calibration, in case the sensor needs to be dismantled before training together with it.

To fix the force, the oar must be loaded stepwise with any available weights (weights, weights, etc.). It is recommended that the number of loading stages is 5–10, the number of loading repetitions is 5–7, the maximum load level is 30–50 % of the maximum expected load at point B when operating the oar during rowing. Preloading should be performed with a load weighing 1–1.5 kg (may be part of a cargo holder) in order to select all gaps in the supports. It is also recommended to perform full loading in idle mode (without removing load cell data). The installation of each of the loads on the cargo holder should be carried out smoothly for no more than 5 seconds, and then maintained under this load for about 3–5 seconds. Thus, the full loading of the paddle will occur within 1–2 minutes, which will not cause the process of short-term creep in the paddle. Between each loading cycle, hold the paddle without load for 2–3 minutes to restore the shape, while not releasing the paddle from the preload.

After completion of all loading cycles, plot the dependence of the load cell output signal on time. If the loading is performed correctly, the graph will represent an alternation of sections of the signal increase with sections of an almost unchanged signal (plateau). Then, on each data plateau, find the average value of the signal corresponding to a certain stage of the paddle load. Build dependencies in the coordinates «average signal value, mV – load, N», check for linear dependence between them, build a trend line, for example, in Excel and determine the conversion coefficient (N/mV) equal to the tangent of the slope of the trend line.

Conclusion

For the first time, a measuring system has been developed and tested to assess the speed and strength fitness of athletes in conditions of rowing locomotions on kayaks and canoes. It is shown that the calibration of the measuring system can be carried out both in a laboratory and in a training base for different models of oars, taking into account the individual characteristics of athletes.

The application of calibration works in any of the three proposed loading schemes, which most fully simulate the operation of an oar in real rowing conditions, is theoretically justified. The choice of the loading scheme is influenced only by the technical capabilities of the instrumentation of the measuring stand or equipment during the calibration procedure of the load cell.

The load cell installation must be oriented relative to the axis of the paddle rod in such a way that it is located above the part of the paddle rod that experiences the greatest tensile deformations during calibration. In the longitudinal direction, the sensor is positioned as close as possible to the point of grip of the paddle by the athlete, without creating discomfort when controlling the paddle.

It has been experimentally proved that the readings of the load cell are significantly influenced by the way it is fixed to the paddle rod. At the same time, the most acceptable scheme is justified, in which one end of the load cell beam is fixed with a metal clamp, providing the greatest adhesion between the beam and the paddle rod, and the other end of the beam is fixed with a pair of plastic ties in combination with an antifriction layer. This method of fastening provides the possibility of longitudinal sliding of the load cell beam relative to the paddle rod when it bends. Thus, a linear relationship between the sensor readings and the external load is guaranteed, as well as good reproducibility of the data.

It is established that in order to carry out calibration using the loading device of the test machine, it is necessary to ensure a constant rate of load increase. This technique greatly simplifies the construction of the "output voltage – external load" relationship and the load cell conversion coefficient. The conversion coefficient in this case is the inverse value of

Table 4

Relative values of the Euclidean metric (10–3 %) for strain gauge data

Mounting method	**Test pairs being compared**									
	1↔2	1↔3	1↔4	1↔5	2↔3	2↔4	2↔5	3↔4	3↔5	4↔5
2	6.19	7.08	8.81	9.95	1.79	3.43	4.48	1.78	2.91	2.91
3	4.37	7.51	7.15	7.79	4.86	5.02	5.82	1.79	2.19	0.66

the tangent of the slope angle of the regression line of the data of the dependence of the output voltage of the load cell on the applied external force.

The results obtained in the framework of the study can also be useful in the design of measuring devices for a similar purpose.

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