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Research of the force characteristics of hydraulic cylinder type loading devices for exercise machines

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1. Introduction

Physical inactivity has been identified as the fourth leading risk factor for global mortality causing an estimated 3.2 million deaths globally [1]. Sport is one of the types of physical activity what is an effort involving the muscle-skeletal system which entails higher energy consumption than that required during rest. For many people it is a major activity which aim is achieving better sports results, but mostly it helps to maintain general physical condition. To help in this wide range of technical equipment may be used from the simplest free weights and elastic bands to universal or specialized power and cardio fitness exercising machines, including computerized trainers-analyzers with electromechanical loading units (Biodex, ConTrex, Humac Norm etc.).

Inter alia this equipment differs by the type of resistance force to be overcome by the athlete: linearly elastic in case of rubber bands or spring expanders, inertial in case of medicine balls, gravitational in weight stack loading machines or special resistance regimes (isokinetic, isotonic) in case of electromechanical systems. One more quite specific type of resistance is hydrodynamic resistance, typical for waterborne sports – rowing and swimming. Such resistance adapts to the natural muscle strength and allows achieving the full muscle load during the entire cycle [2]. Therefore, recently hydraulic cylinder (HC) type devices (or shock absorbers) started to be used in sports and rehabilitation exercise machines. Such devices are especially suitable for rowing exercisers (Fig. 1, a), because the pattern of the resistance on the oar handle during the stroke is very similar to real rowing – depends on the velocity of its movement (viscous resistance) [3, 4]. They are also used in steppers (Fig. 1, b), selectorized equipment for training separate groups of muscles and universal exercise machines.

The resistance force in hydraulic cylinder is obtained by forcing viscous liquid flow from one chamber of

Fig. 1 Exercise machines with HC type loading units: a – lever type rowing simulator; b – mini stepper

cylinder into another through small cross-section channels in the piston or the end caps of cylinder by moving HC piston by the handles or treadles of exercisers, thus hydrodynamic resistance is directly dependent on the actuation speed, piston diameter, number and dimensions of the bypass channels (or their total cross-section area) and the viscosity of the hydraulic liquid). Hydraulic cylinders used in sports equipment may generate resistance force in one or both directions (in the latter case – either equal or different during forward and backward strokes). Some of them are supplied with mechanisms for setting different level of resistance by rotating ring controlling the cross-section of the bypass channels connecting the chambers of cylinder (rowing machine Kettler Kadett). Constant nominal force cylinders may be mounted in exercisers with possibility to change lengths of the levers connecting cylinder to exerciser (rowing machine Kettler Favorit). Constant nominal resisting force hydraulic cylinders are also used in simplest mini steppers. In more complex and expensive, like Tunturi pro Climber (independent stepping action), manually adjusted units may be installed.

In case of simplest types of the resistance (elastic, inertial, gravitational) its variation during the stroke may be determined quite precisely and is usually known, but when more cumbersome mechanical devices like hydraulic cylinders are involved situation becomes more complicated. Anyway it is quite important to have it when developing exercisers ensuring possibility to train not only the strength and endurance but also the technique and coordination of movements, what is very important, for example, for rowing (sculling) [5-7].

The aim of this research was to examine the characteristics of resistance force (force dependencies on piston displacement) generated by linear hydraulic cylinder type loading devices of exercisers acting in different regimes (resistance level and piston speed). The dependencies of the resistance force generated by the hydraulic cylinders of six different exercises machines on the speed of movement of the piston and on the resistance level have been investigated experimentally.

2. Methods and means

The objects of the research are hydraulic cylinders of rowing simulators and mini steppers which main parameters are as shown in Table. The main parts of the twin-tube linear adjustable resistance force HC are its body consisting of two tubes (external and internal) joined by two endcaps. One of them is equipped with resistance adjustment unit – flow control valve, and the opposite has check valve, which opens when the piston is extracted (work phase of rowing stroke).). Piston sliding within internal tube is also equipped with check valve, which opens when piston is inserted (idle run or recovery phase of rowing), During power stroke the piston, being extracted via piston rod, makes the oil to flow from the chamber within internal tube to the chamber between internal and external tubes through the flow control valve separating these chambers. The flow through this valve is controlled by setting cross-section area of the channel within flow control valve (turnable disk having circular grove of variable width and depth with regard to input and output openings of the valve is used mostly). In this case resistance force may be regulated evenly, 12 resistance levels marked on control ring are only conditional.

Table

Main technical parameters of the HC of exercisers

Parameter \ Cylinder	Rowing simulator			Stepper
	No.1	No.2	No.3	No.4-6
Number of levels of resistance	12			1
Stroke, mm	285	275	265	120
Minimal distance between the centers of mounting hubs, mm	460	415	465	210
Cylinder external diameter, mm	45			38
Piston diameter (cylinder bore), mm	25			
Working stroke	Piston extraction (extension)			Piston insertion (compression)

Such twin-tube design ensures ability to cool the oil effectively, which is necessary because of the regime of usage of such devices – exercising usually means hundreds or even thousands of stroke cycles, and oil circulating within such cylinder due to internal friction may get warm up to near 100ºC, thus changing resisting abilities of the cylinder and even becoming unsafe to use it.

Design of the smaller cylinders for steppers is simpler due to absence of the resistance adjustment unit. Also the regime of operation of the check valves in the piston and in the end of the cylinder is different due to opposite direction of the working stroke: hydraulic cylinders in rowing machines resist when being extended and in steppers – when compressed (or piston extracted or inserted correspondingly).

To determine resistance force characteristics of hydraulic cylinder type resistance devices of six exercise machines – lever type rowing (sculling) simulators (No. *1*, *2* and *3*, adjustable force, 12 resistance levels, Fig. 2) and steppers (No. *4*, *5* and 6, Fig. 2), the measurements of dependencies of resistance force of HC on the run of the piston at different operating regimes have been performed by using the test rig shown in Fig. 3.

Hydraulic cylinders were tested by means of universal computerized two columns benchtop materials testing machine „Tinius Olsen H25KT“ (Tinius Olsen, USA), controlled by the software QMAT (also used for processing measurements data). The measurements were carried out with the machine being in horizontal position due to the reason that hydraulic cylinders in exercise machines usually operate in this position or close to it.

Fig. 2 Hydraulic cylinder type resisting devices for exercisers: rowing simulators (No. *1-3*) and steppers (No. *4-6*)

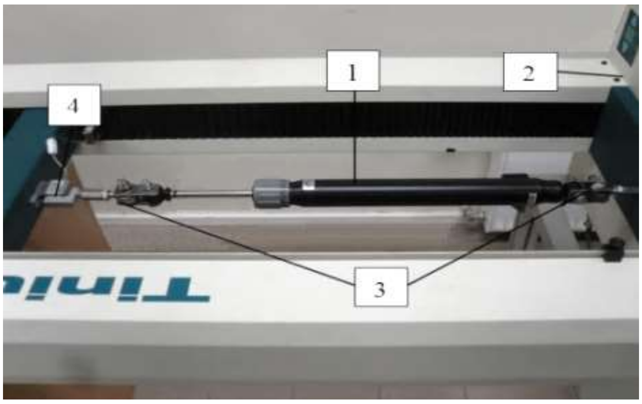

Fig. 3 Test rig for resistance force characteristics analysis of hydraulic cylinders: *1* – hydraulic cylinder; *2* – testing machine Tinius Olsen H25KT; *3* – spherical bearings; *4* – force sensor HTE-1000N

The stroke of HC piston (corresponding the displacement of cross arm of the machine) and the force generated by HC were measured synchronically by internal measurement system of the machine (1000 N capacity force sensor THE-1000N was used).

The hydraulic cylinders were attached to the base of the machine and to the force transducer (attached rigidly to the cross arm of machine) at their mounting hubs via spherical bearings thus avoiding possible flexion of the cylinder due to non-axial loading.

The variation of resistance force during cylinder stroke (200 mm – rowing exercisers, 80 mm – steppers) was measured at different piston speed (60, 300, 600, 900 mm/min), for rowing simulators – additionally at different resistance levels (I, IV, VIII, XII, set by resistance adjustment unit, repeating each test three times at constant environmental temperature (20ºC).

3. Results

Variation of the resistance forces generated by HC of rowing machines No. *1*, *2* and *3* (piston extraction) and steppers No. *4*, *5* and *6* (piston insertion) measured during constant speed travel of the piston (at constant 20ºC temperature) are shown (Figs. 4 and 5).

The dependencies of resistance force on travel of piston at four different speeds – 60, 300, 600 and 900 mm/min for adjustable rowing machine cylinders are shown on Fig. 4, a, c, e (left column subfigures) and for mini-steppers cylinders – on Fig. 4, b, d, f (right column figures). Characteristics of the cylinders of rowing machines corresponds the case when the resistance level VIII (of twelve available) was set on force adjustment unit during measurement.

It was found that force characteristics of all adjustable HC for rowing exercisers apparently differ both qualitatively and quantitatively (Fig. 4, a, c, e). In one case force jumps to close to nominal value immediately after the piston starts to move and oscillates until piston travels near 100 mm (Fig. 4, a), in second – reaches nominal value gradually within piston travel near 10 mm and fluctuates heavily (Fig. 4, c). Practically stable nominal resistance force is ensured during stroke of HC No. *3*, but the time until it is reached and corresponding piston displacement

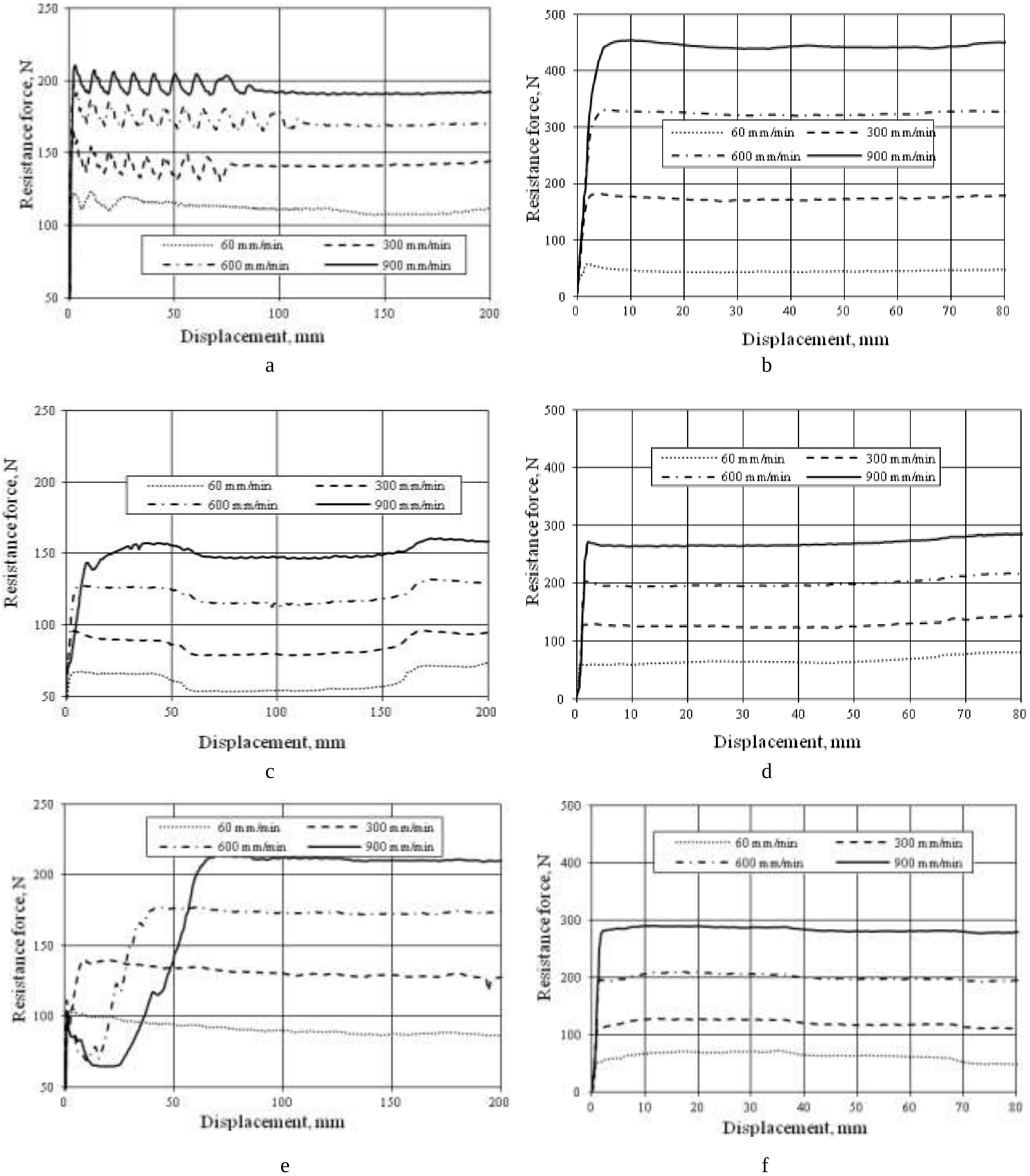

Fig. 4 Resistance force w.r.t. displacement for the hydraulic cylinders of exercise machines: rowing simulators (left column figures a – cylinder No. *1*; c – No. *2*; e – No. *3*) with resistance level set to VIII position; and steppers (right column figures b – cylinder No. *4*; d – No. *5*; f – No. *6*) at the constant piston speeds (60, 300, 600 and 900 mm/m)

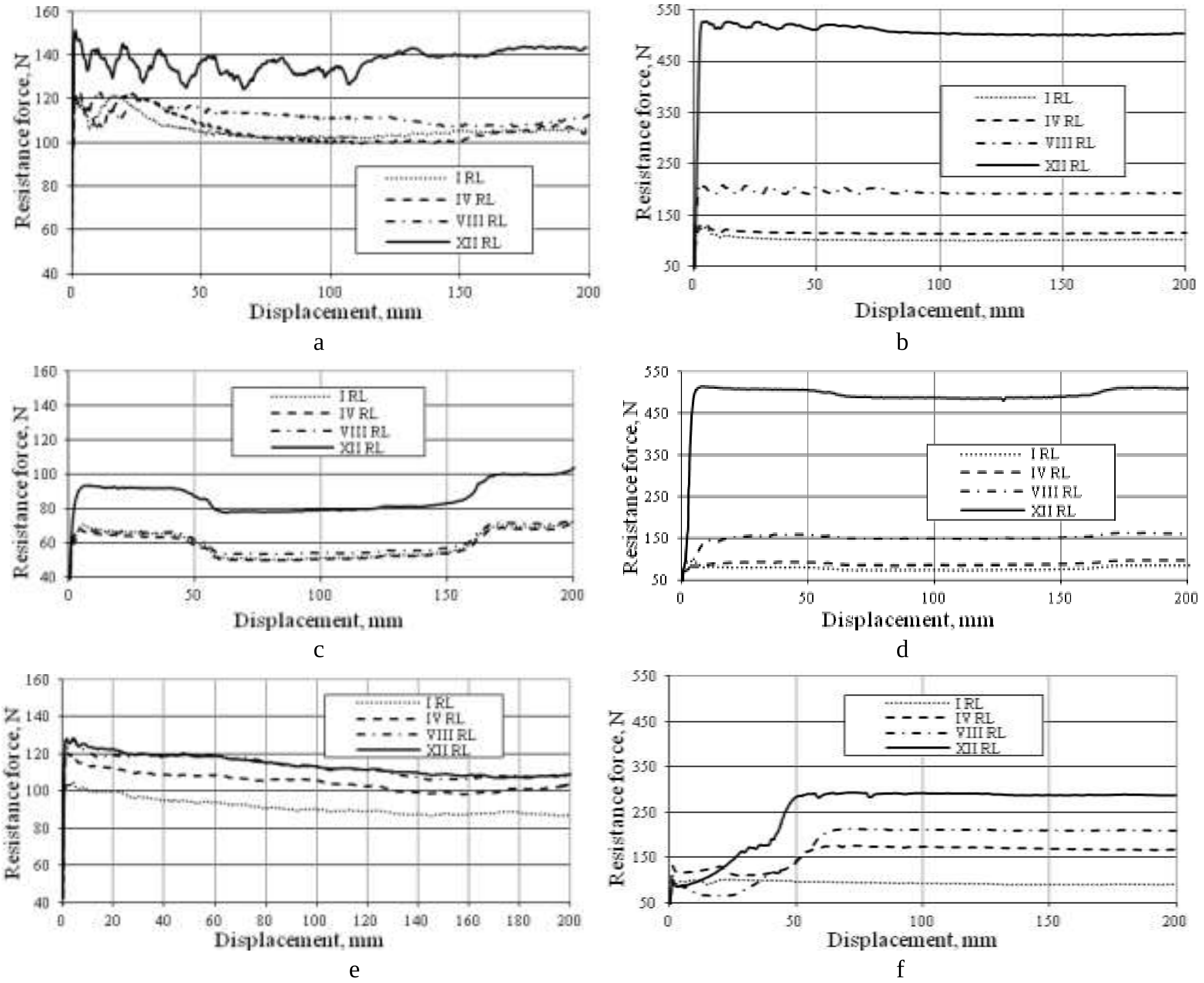

Fig. 5 Resistance force w.r.t. displacement of piston for the hydraulic cylinders of three rowing machines: No. *1* (top row figures, a and b); No. *2* (middle row figures, c and d); No. *3* (bottom row figures, e and f) at different piston speed (left column figures, a, c, e – piston speed 60 mm/min; right column figures b, d, f – 900 mm/min) and different resistance levels (I, IV, VIII and XII)

are significantly larger than for first two cylinders (Fig. 4, d). Such instability (during the stroke) of the force characteristics of rowing exercisers and differences of nominal resistance force at different speed of the piston may be caused by design features of the cylinders, namely – check valves and resistance adjustment unit. Nominal resistance force generated by hydraulic cylinders of different rowing machines was from 50 – 110 N at the lowest speed of the piston (60 mm/min) to 150 – 210 N at the highest speed of the piston (900 mm/min) the diameter of the piston being the same for all of them and the same resistance level (VIII) set during the tests (Fig. 4, a, c, e). It increases proportionally to the growth of speed of the piston for all three cylinders. Steppers cylinders gave nominal force correspondingly from 50-70 N to 270-450 N (Fig. 4, b, d, f).

Such differences in size of nominal force of the cylinders of rowing machines may be explained by the fact that they are taken from the exercisers having different size arms of the levers to which HC are attached, so it is quite important to use proper cylinder when replacing broken or worn one. Unfortunately none of them is supplied with information about their capacity.

Force characteristics of steppers cylinders are far smoother (Fig. 4, b, d, f) than of cylinders of rowing machines (Fig. 4, a, c, e). Nominal force is reached within the stroke up to 5-10 mm and remains practically stable during piston travel. Its size also differs – from near 300 N (two examined cylinders) to near 450 N. One of these cylinders gave near 50 % higher nominal force at the higher piston speeds than other two (No. *4*, Fig. 4, b).

Fig. 5 shows the characteristics of resisting force generated by HC of main object of the research –rowing machines No. *1*, No. *2* and No. *3* obtained at different resistance levels set by adjustment unit (I, IV, VIII and XII). Each cylinder is characterized by two figures in corresponding row (No. *1* – top row figures, a and b; No. *2* – middle row figures, c and d; No. *3* – bottom row figures, e and). Each row figures shows corresponding two piston speeds – 60 and 900 mm/min (left and right columns figures correspondingly).

The research showed that only cylinder of the exercise machine No. *3* ensures possibility to adjust the resistance force proportionally to the resistance level set by control ring on hydraulic cylinder (Fig. 6, e, f). Other two cylinders showed less sensitivity to position of adjusting ring at the lowest resistance levels (Fig. 6, a, b and c, d). In addition, resistance force at the same resistance level differs significantly: cylinder No. 3 gives near only a half of force generated by cylinders No. 1 and 2 at the same piston speed and resistance level set. Thus even if the design and kinematics of all rowing exercisers seems to be very similar, the resistance on the oar handle may be quite different for different exercisers even at the same resistance level. In addition, the resistance force characteristic may differ from the hydrodynamic resistance law ensured when rowing real boat, what means that such cylinders are not able to simulate real rowing conditions in full scale.

4. Discussion

Rowing is seasonal sport, thus rowing simulators are widely used for indoor training amateur and professional rowers. One of the most actual problems when training advanced athletes is the reproduction of the physics of rowing, i.e. the rowing kinematics and the pattern of resistant force, because these factors have quite large influence on rowing performance [5-11]. Therefore when the own weight or similar simple rowing machines are enough for maintaining general physical condition, professional athletes prefer improving their physical abilities and technique by rowing a boat fixed in the pool [12], where the kinematics of movements and the variation of resistance force conforms the real rowing. But such equipment seems to be too cumbersome and too expensive (especially when there is a need to train in the sports club or at home). More acceptable solution of the problem is well-known rowing simulators “Concept2” or “Rowperfect” where resistance is generated by a flywheel equipped with adjustable air turbine. But both of them are operated by handle, pulled by both hands, and trajectory of movement is also not quite the same as in sculling boat, thus they also reproduce the physics of the rowing only partially.

Lever type rowing simulators, like Kettler’s Kadett, Hammer Rower Cobra, HCI Sprint Outrigger etc. are free of deficiencies mentioned above, and their resistance generating devices on principle should ensure pattern of resistant force very similar to real rowing. However, the results of the research performed show that variation of the resistant force at constant piston speed is quite significant (especially – for adjustable cylinders), so it is difficult to recommend such devices to the top level athletes seeking maximal performance not only in strength but also in improving technique. In addition, these or other “dry” rowing simulators have no possibility to ensure control of the resistance during stroke. The resistance level can be set prior the exercise, but it cannot be adjusted during the exercising process, what is quite important when developing rowing simulators or exercise machines for rehabilitation. Such exercising machines should be able to generate resistance force according the necessary law and could operate at special (isokinetic, isotonic regimes or similar) regimes.

That’s why the development of rowing machines, able to reconstruct the conditions of real rowing is carried out in Kaunas University of Technology. At first controllable resistance force unit based on the rotational hydraulic cylinder, equipped with a proportional flow control valve [13], has been designed. According to the principle of operation it was quite similar to the linear cylinder described above, but theoretically possessed ability to control the resistance force during the stroke. However, it has appeared that such device is too complex, so researches have been reoriented to linear cylinders. The results of research described above proved the necessity of more precise control of the resistance force in linear motion hydraulic cylinder type loading units of rowing simulators. Thus recently the linear motion hydraulic cylinder type loading device operating on the basis of active material (magnetorheological fluid) has been developed [14] allowing the formation of controlled resistance according the desired law both during a cycle and in between cycles. Unlike in mechanically controlled cylinders described in section 2, in the latter case the resistance is controlled by changing the strength of applied electromagnetic field acting the magnetorheological fluid within the cylinder. Such approach leads to higher effectiveness of the control and the smoother pattern of the resistance force and allows compensation of the variation of the viscosity of fluid due to change of its temperature during training process. However in case when such sophisticated (controllable resistance) equipment is not necessary, it is very important to use identical cylinders in pairs thus ensuring symmetry of exercising.

5. Conclusions

1. Hydraulic cylinders of rowing simulators generate quite uneven resistance force: its characteristics are different both in the very beginning of the stroke and until piston stops. Depending on the operation regime, variation of resistance force reaches up to 30% of nominal force at constant piston speed, while unadjustable cylinders of steppers gave practically stable resistance.

2. Nominal resistance force generated by hydraulic cylinders of different rowing machines is also quite different (from 50 – 110 N at the lowest speed of the piston to 150 – 210 N at the highest speed of the piston, resistance level VIII), it increases proportionally to the growth of speed of the piston for all three cylinders. Steppers cylinders gave nominal force from 50-70 N to 270-450 N depending on piston speed.

3. The resistance adjustment units of HC of rowing exercisers ensure possibility of setting nominal resistance force level, however its size differs significantly for different cylinders (at same level set). Resistance force sensitivity to the position of adjusting ring is not linear for two of three examined devices (is practically inconsiderable at lowest levels of resistance).

4. It may be stated basing on the results of investigation that the nominal resistance force on the lever representing oar handle of rowing exercisers depend on the cylinder used (is different for the same design cylinders of different vendors), so it is important to use proper cylinder when replacing broken or worn one or both cylinders are to be replaced to ensure symmetry of loading. In case when higher level of similarity to real rowing is necessary, the more sophisticated controllable resistance force cylinders (for example, magnetorheological) should be used.

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References

1. World Health Organization. http://www.who.int/topics/physical_activity/en/. Accessed 25 April 2014.
2. **Zatsiorsky, V.M.** 1995. Science and practice of strength training. Human Kinetics, 243p.
3. **Flood, J.; Simpson, C.** 2012. The complete guide to indoor rowing. Bloomsbury publishing Plc.
4. **Pulman, Ch.** The Physics of Rowing. Gonville & Caius College, University of Cambridge. http://www.atm.ox.ac. uk/rowing/physics/rowing.pdf. Accessed 25 April 2014.
5. **Bartlett, R.** 1999. Sports biomechanics: preventing injury and improving performance. Routledge, New York, 276p. http://dx.doi.org/10.4324/9780203474563.
6. **Baudouin, A.; Hawkins, D.** 2002. A biomechanical review of factors affecting rowing performance, Br. J. Sport Med. 36(6): 396-402. http://dx.doi.org/10.1136/bjsm.36.6.396.
7. **Kleshnev, V.** 2010. Boat acceleration, temporal structure of the stroke cycle, and effectiveness in rowing, Journal of Sports Engineering and Technology 224(1): 63-74. http://dx.doi.org/10.1243/17543371JSET40.
8. **Marinus Van Holst**. On Rowing. Revision 2009. http://home.hccnet.nl/m.holst/RoeiWeb.html. Accessed 25 April 2014.
9. **Smith, R.M.; Spinks, W.L.** 1995. Discriminate analysis of the biomechanical difference between good novice and elite rowers, Journal of Sports Sciences 13: 1-9 and 377-385. http://dx.doi.org/10.1080/02640419508732253.
10. **Andrews, B.J.; Hase, K.; Halliday, S.E.; Zavatsky, A.B.** 2002. Biomechanical study of FES rowing and inclined bench sliding systems using simulation models. 7th Annual Conference of the International Functional Electrical Stimulation Society (Ljubljana): 347-349.
11. **Hislop, S.; Cummins, K.; Bull, A.M.J.; McGregor, A.H.** 2010. Significant influence of the design of the rowing ergometer on elite athlete kinematics, Journal of Sports Engineering and Technology 224(1): 101-107. http://dx.doi.org/10.1243/17543371JSET54.
12. A Legacy of Support to Academics and Athletics. Indoor rowing pool. http://www.northeastern.edu/leadershipcampaign/donors/barletta.html. Accessed 25 April 2014.
13. **Dervinis, G.; Šarkauskas, K.K.; Grigas, V.; Toločka, R.T.** 2011. Controllable hydraulic loading unit for rowing simulator, Electronics and Electrical Engineering, 10(116): 59-62. http://dx.doi.org/10.5755/j01.eee.116.10.881.
14. **Šulginas, A.** Design and research of magnetorheological loading units for training equipment. Summary of Doctoral Dissertation. Accessed 25 April 2014. http://en.ktu.lt/sites/default/files/A.SULGINO%20 Santrauka_en_2013%2004%2016.pdf.

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TRENIRUOKLIŲ HIDRAULINIO CILINDRO TIPO APKROVOS ĮRENGINIŲ PASIPRIEŠINIMO JĖGOS CHARAKTERISTIKŲ TYRIMAS

R e z i u m ė

Įvairiais režimais veikiančių treniruoklių hidraulinio cilindro tipo apkrovos įrenginių pasipriešinimo jėgos charakteristikų eksperimentinis tyrimas atliktas medžiagų mechaninių savybių nustatymo mašina Tinius Olsen H25K-T. Ištirta po tris skirtingų gamintojų cilindrus, naudojamus žingsniuokliuose ir irklavimo treniruokliuose (pastarieji – reguliuojamo pasipriešinimo). Tyrimų rezultatų pagrindu galima teigti, kad treniruokliuose naudojami hidraulinio cilindro tipo pasipriešinimo įrenginiai generuoja gana netolygią pasipriešinimo jėgą: priklausomai nuo darbo režimo jos kitimas esant pastoviam stūmoklio judėjimo greičiui siekia iki 30% nominalaus dydžio. Vienodos konstrukcijos skirtingų gamintojų cilindrų nominali pasipriešinimo jėga yra skirtingo dydžio, skiriasi ir jos kitimas darbo eigos metu, todėl keičiant susidėvėjusį ar sugedusį cilindrą siekiant užtikrinti pasipriešinimo simetriškumą svarbu naudoti tinkamą cilindrą arba keisti abu cilindrus.

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RESEARCH OF THE FORCE CHARACTERISTICS OF HYDRAULIC CYLINDER TYPE LOADING DEVICES FOR EXERCISE MACHINES

S u m m a r y

Experimental research of hydraulic cylinder type resistance devices at different operating regimes (piston speed and resistance level) has been performed by means of universal computer controlled benchtop materials testing machine “Tinius Olsen H25K-T”. The samples were taken from different brands exercisers where resistance is generated by the pair of cylinders: three mini steppers and three rowing exercisers (these with manually adjustable resistance). The research showed that hydraulic cylinder type loading devices of exercise machines generate quite uneven resistance force: depending on the operation regime its variation reaches up to 30 % of nominal size. According to the results of investigation it may be stated that the nominal resistance force depend on the cylinder used (is different for the same design cylinders of different vendors), so it is important to use proper cylinder when replacing broken or worn unit or even both cylinders have to be replaced to ensure symmetry of resistance.

Keywords: hydraulic cylinder, exercise machine, resistance force, piston speed.

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