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Inertial load stabilization in free load exercise machines

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1. Introduction

Muscle loading force in exercise machines is created in different ways, based both on the type of machine and design solutions: weight stack gravity force, magnetic field resistance [1-6], fluid flow resistance force, belt friction force, compressed air drag and otherwise [7].

Besides general purpose, there are also specialized exercise machines, simulating certain human motions: skiing, rowing and even swimming [2, 6]. But the most of traditional devices are not enough accommodated for the improvement or training special or technical skills of athletes. Such simulators usually train one or more muscle groups, without giving details of individual muscle activity and avoiding the excessive load variation during exercise.

Currently simulators with more sophisticated load-generating units are used more widely, most of them having a feedback between the input link movement and the generated load [8-9] and the possibility to control the load. Muscle load can be changed within each exercise step (cycle) or after performing a certain number of those movements with regard to functional parameters of the trainee.

There are many companies in the world producing various inertial force simulation machines: PRECOR [10], BOWFLEX [11], POWER SYSTEMS [12], KINGS OF CARDIO [13]. The greatest disadvantages of those exercise machines are uncontrolled muscle load variation due to the action of inertia forces and the lack of possibility to adopt load to the specific needs, what undoubtedly may be accessed by using load stabilising and control devices.

An attempt to improve such exercise machines by introducing equipment allowing to control or stabilize the load, generated by moving weight, is described in this paper.

2. Stabilization of inertial load in exercise machines

The most popular scheme of the weight machines is the one where the athlete lifts weight stack by pushing or pulling the lever, to which the weight stack is connected by cable guided by pulleys. When moving the handles of the simulator, the constant mass stack moves with acceleration, as the result giving a variable load force (Fig.1) [14].

The inertial load can be controlled in simulators in order to make the exercising process more efficient. It can be stabilized using a spring-loaded roller, interacting with the flexible coupling of the simulator (Fig. 2) or controlled by a special actuator that implements the chosen law of motion (Fig. 3).

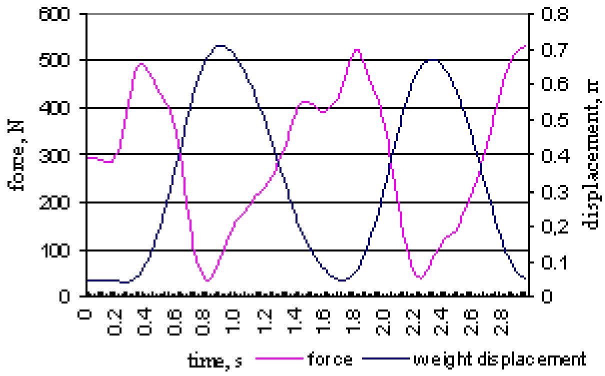

Fig. 1 Variations of weight displacement and force on handle over time when pulling the handle of weight machine (two cycles)

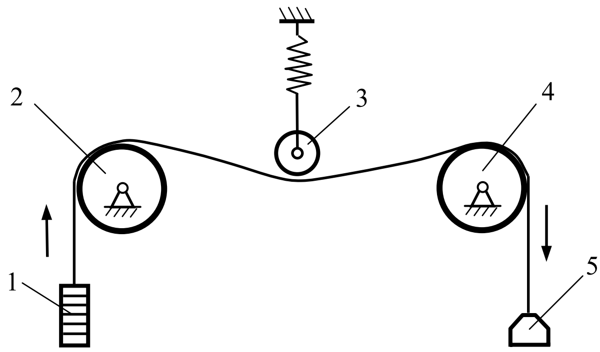

Fig. 2 Inertial load stabilization by spring roller: *1*- weight, *2, 4* - pulleys, *3* - spring-loaded roller, *5* - handle

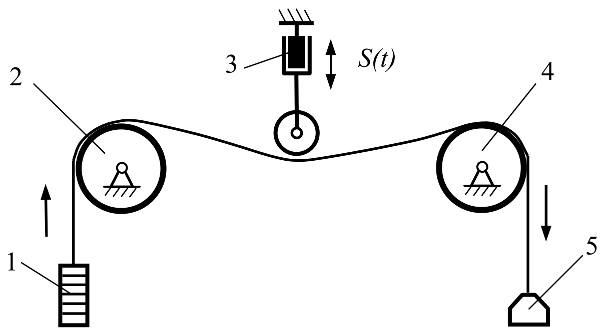

Fig. 3 Inertial load control by additional actuator: *1* - weight, *2, 4* - pulleys, *3* - additional actuator, *5* - handle

Load stabilization possibilities by means of a spring-loaded roller can be proved by using the model, shown in Fig. 4.

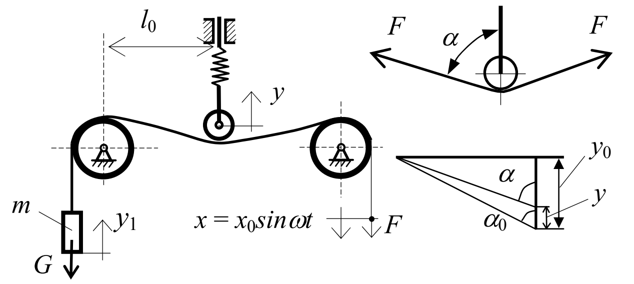

Fig. 4 Simplified model of loading system with spring-loaded roller

The spring - loaded roller motion can be described by the following equation

$$cy = 2\left(G + m\ddot{y}_1\right)\cos\alpha_0 \tag{1}$$

where c is the spring stiffness; G is load weight; m is load mass; α_0 is nominal span angle (assumed that $\alpha \approx \alpha_0$); y and y_1 are weight and roller displacement

$$y_1 = y - 2s \tag{2}$$

where s is the handle displacement.

The solution for harmonic excitation $s = s_0 \sin\omega t$ is

$$y = \frac{g\cos\alpha_0}{2\omega_0^2} + \frac{s_0\cos\alpha_0}{2\left[1-\left(\frac{\omega_0}{\omega}\right)^2\right]}\sin\omega t \tag{3}$$

where g is the acceleration of gravity; $\omega_0 = c/4m$ is the natural frequency of the dynamic system.

Solution (3) allows us to define the force acting on the handle

$$F = G + m(\ddot{y} - 2\ddot{s}) = mg - mx_0\omega^2\left[1 + \frac{1}{1-\left(\frac{\omega_0}{\omega}\right)^2}\right]\sin\omega t \tag{4}$$

Finally the condition of stabilizing effect of inertial load may be defined

$$c > 8m\,. \tag{5}$$

3. Experimental test bench and measurement equipment

For the experimental research of weight machine equipped with a spring - loaded roller stabilizer the test bench was designed by means of 3D CAD software SolidWorks (Fig. 5).

According to computer model the experimental test bench has been made meeting the principle of operation of inertia load exercise machine (Fig. 6). Five steel plates, each weighing 1.3 kg, are used for the loading. To check mathematical model described in Section 2 the exciter is designed consisting of electric motor (power of 0.55 kW, rotation speed 60 min^{-1}) with gearbox and crank mechanism, giving the harmonically varying kinematic excitation on the input ("handle") of the test bench (the duration of loading cycle and magnitude of kinematic excitation are set similar to the values obtained when performing exercises of pulling the handle by hand). The stack of plates is attached to the exciter via the flexible cable guided by two pulleys. In the middle of the span between pulleys (1.0 m.) the cable is deflected in perpendicular direction by the spring - loaded roller.

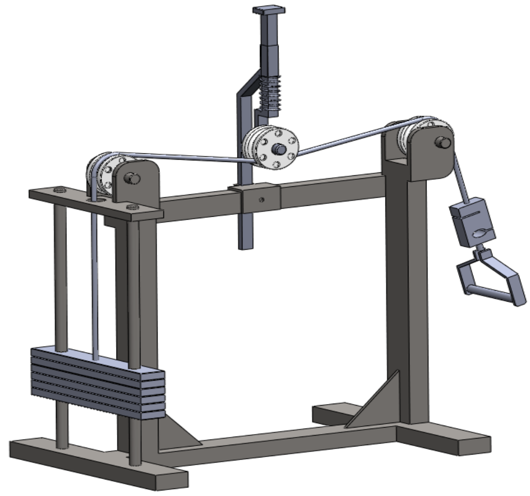

Fig. 5 Computer model of the test bench

To define the main kinematical and force parameters the measuring equipment was implemented (Fig. 6.) to the test bench. Thus the input force ("on handle" or near the force generator) has been measured by tensometric force gauge, attached to the portable computerised multichannel measuring chain Spider Mobil (HBM, Germany), and synchronically - the kinematic parameters of movement of the loading plates, exciter and the stabilizer roller have been measured by means of 3D motion Capture system (Qualisys, Sweden).

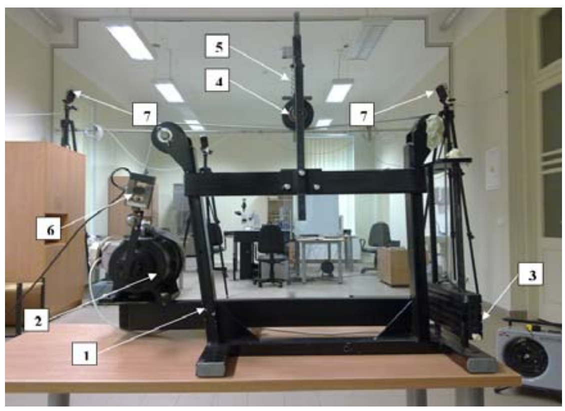

Fig. 6 Bench of test: *1* - frame, *2* - exciter electric motor with gearbox, *3* - weight stack, *4* - roller, *5* - spring, *6* - force gauge, *7* - video cameras of motion capture system

The force gauge S9 (HBM, Germany) was used for the force measurements: nominal force F_{nom} - 500 N, accuracy class - 0.05, sensitivity C_{nom} - 2 mV/V, relative tensile/compression sensitivity difference $dzd < \pm 0.1\%$, nominal shift $S_{nom} < 0.4$ mm.

The 3D video MoCap system Qualisys (6 digital infrared cameras Pro-Reflex) was used for capturing motion parameters (translations, velocities and accelerations) of characteristic points of the test bench where the 15 mm diameter reflective markers were affixed. The maximal measurement frequency of the system 500 Hz (100 Hz frequency was used), measurement range: 0.2 - 70 meters, horizontal field-of-view: 10° to 45°, effective resolution – 20000×15000 subpixels, exposure time -100 - 400 µs.

4. Results of experimental tests

During the preliminary research the "exercising" was simulated by means of the mentioned exciter, generating 1 Hz frequency and 100 mm amplitude harmonic kinematic excitation on the handle of exercise machine.

Such tests were carried out with and without the spring-loaded roller stabilizer. The maximal force amplitude was obtained when the "exercising" was performed on weight machine in the "normal" mode, that is with no stabiliser - 112.4 N, while implementation of the stabilizer reduced maximum values of the force by 20% to 92.3 N (Fig. 7), thus confirming the effectiveness of the stabilizer.

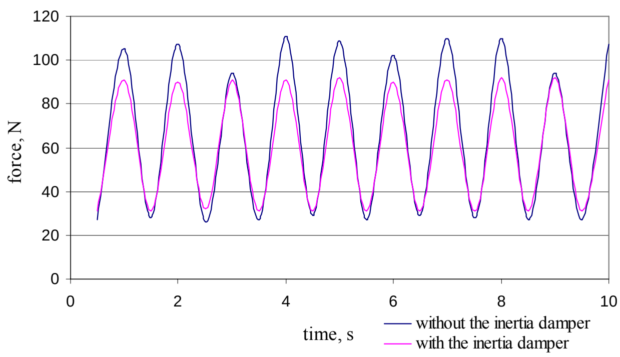

Fig. 7 The force on the handle of weight machine with and with no stabilizer

After verifying that the system with the stabilizer is running efficiently, further tests of the weight machine kinematical and force parameters were performed.

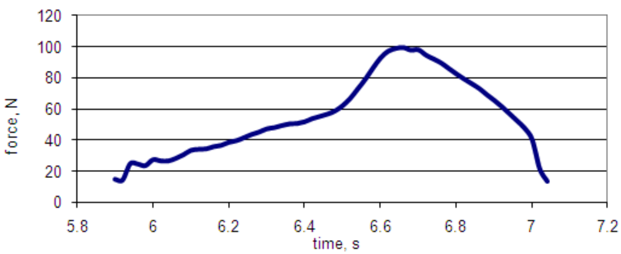

Fig. 8 Force on handle of exerciser without stabiliser when pulling it by hand (one cycle)

Namely, the force on the handle has been measured when pulling it by hand when bending the arm in elbow (mass of the weight stack - 3,9 kg, an athlete's elbow rests on the table during exercise) (Fig. 8), the law of motion of the roller of the stabiliser (Fig. 9) and the handle of exerciser have been determined (Fig 10 and 11).

For investigations of the system without stabiliser, the law of input link motion was determined by using the

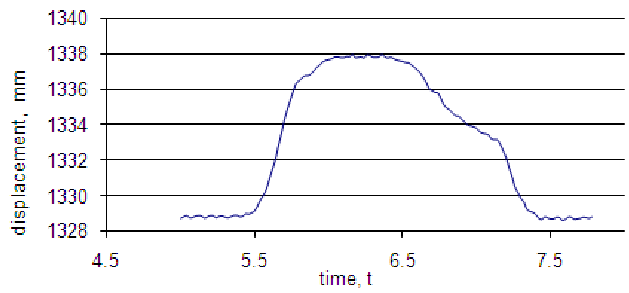

Fig. 9 Law of motion of the roller of the stabilizer during exercise

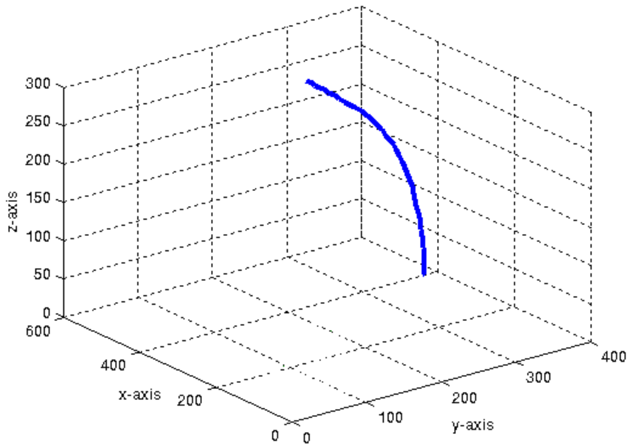

Fig. 10 Trajectory of the handle of weight machine during exercise

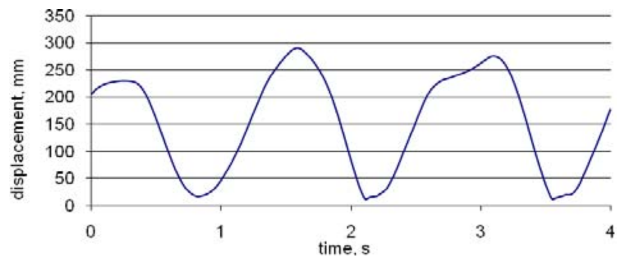

Fig. 11 Law of change of vertical displacement of weight machine handle during exercise

same video equipment, when the reflective bead was attached to the handle.

5. Conclusions

1. The test bench of the inertial weight machine exerciser with a spring loaded roller stabiliser has been developed and experimental research of the kinematic and force parameters has been carried out.

2. The force developed by the inertial weight machine exerciser may differ significantly in comparison with the nominal value of the weight of the plates stack because of inertial loading.

3. The force developed by the inertial weight machine can be effectively smoothened by means of the stabiliser, and controlled by the additional actuator equipped with the control system.

4. The hand loading, its motion and stabilising system kinematic properties were determined experimentally and will be used for the subsequent research.

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TRENIRUOKLIŲ INERCINĖS APKROVOS STABILIZAVIMAS

R e z i u m ė

Moksliniu ir techniniu požiūriu labai svarbu kurti ir tobulinti tokią sporto įrangą, kuri įgalintų treniruotis bei testuoti individualiai pagal vartotojo poreikius, leistų kontroliuoti bei valdyti treniruotės procesą. Šiame straipsnyje aprašomas vienas iš galimų būdų stabilizuoti jėgos treniruoklio inercines apkrovas. Tam tikslui sukonstruotas tyrimų stendas, leidžiantis išmatuoti pasipriešinimo jėgą bei įvairių sistemos dalių (svarmenų, stabilizatoriaus, rankos) judesių kinematinius parametrus. Išanalizavus gautus duomenis, pasiūlytas būdas treniruoklio sukuriamai apkrovai stabilizuoti pasyviu stabilizatoriumi. Pirminiai eksperimentinių tyrimų rezultatai patvirtino tokio stabilizatoriaus naudojimo efektyvumą.

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INERTIAL LOAD STABILIZATION IN FREE LOAD EXERCISE MACHINES

S u m m a r y

From the scientific and technical point of view it is very important to develop such type of training equipment which would allow us to exercise and perform tests individually according to the needs of each user, and control and manage the entire training process. The paper describes the possibilities to stabilize the inertial load in the simulator and control it. The test bench was designed, allowing measurement of the resistance forces and kinematic parameters of various parts of the system (weights, stabiliser, handle). The preliminary result of experimental investigations has proved the effectiveness of the developed passive stabiliser.

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