Rotating training simulator – an apparatus used for determining the moment of inertia, assisting learning various motor activities during rotational movements and simulating falls imposed by internal force

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Abstract

One of the three factors identifying forms of extreme physical activity (including extreme sports) is 'coordination difficulty'. The aim of the present paper is to recommend the rotating training simulator as an apparatus that can exercise three functions: determining the moment of inertia, improving motor habits while performing certain "rotation techniques" in various sports disciplines, simulating the effect of the external force as the cause of losing balance and falling by a man who originally was immobile (standing, sitting, kneeling etc). The apparatus consists of a rotating platform, which for measuring the moment of inertia is driven by the action of a falling mass. In a training mode the device can also be driven by an electric motor. The measurement of the speed of the rotating platform with a subject placed on it is done by an encoder connected to a logic controller PLC. The controller through a serial interface connector is connected to a PC computer which records the results of measurements and saves them in the archives. Recording of the subjects' positions assumed on the training simulator is performed by using a video camera. This makes it possible to compare the obtained picture record with the record of the angular velocity obtained at the same time and thus to analyse the correlation between the reached angular velocity with the assumed body position. An example of determining the moment of inertia of a person for the body position in break dance using the training simulator, as well as visualisation (graphical and filming) of the training simulator applications in a training mode provides, in the author's opinion, sufficient arguments for proving the apparatus usability for scientific research and training. The apparatus can successfully attend to improving our knowledge of phenomena related to rotational movements of a human being and of his adapting abilities to motor activities with frequent occurrence of such events. The increased probability of a person finding himself in such a situation contrary to the subject's (individual's or a team's) will is especially common for soldiers, policemen, rescuers etc. and that is why the training simulator can be used as an apparatus assisting training of members of such formations.

Key words: biomechanics • moment of force • motor safety • sports techniques

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Abilities (motor abilities) – Stable, enduring traits that, for the most part, are genetically determined and that underlie a person's skill in a variety of tasks. People differ with respect to their patterns of strong and weak abilities, resulting in differences in their levels of skill [19].

Posture – noun the position in which a body is arranged, or the way a person usually holds his or her body when standing [20].

Position – noun 1.the place where a player is standing or playing 2. the way in which a person's body is arranged [20].

Technique – noun a way of performing an action [20].

Sports technique – a method of performing a motor task specified in the rules of a given sports discipline that depends on particular athletes' somatic, motor and psychic properties [21].

Rotary technique – a method of performing a motor task involving rotational movement following the accepted motor pattern in particular sports disciplines, motor recreation forms as well as in doing a job.

Motor safety – is consciousness of the person undertaking to solve a motor task or consciousness the subject who has the right to encourage and even enforce from this person that would perform the motor activity, who is able to do it without the risk of the loss of life, injuries or other adverse health effects [22].

Moment of force – it is the cross product of the lever-arm distance vector r with the beginning in 0 and the end in the point of applying force, and the force F (M= F x r) [23].

INTRODUCTION

One of the three factors identifying forms of extreme physical activity (including extreme sports) is "coordination difficulty" [1]. Paradoxically, in certain circumstances even a very high coordination difficulty (for example, in circus shows) does not constitute any threat to health or life of people who have been properly trained, whereas under other circumstances (for example, in rescue operations [2]) even a simple motor activity can constitute such a risk. Although a man can master, in terms of coordination, even very difficult exercise routines through many years' practising, unfortunately, he is not able to predict nor repeat within the course of training the situations, which under some circumstances can happen and present threat.

Both sports athletes, circus artists and stunts etc., as well as soldiers, policemen, firemen, rescuers etc., use various devices (training simulators), which are supposed to improve training effects enormously. In many sports disciplines (figure skating, artistic and sports gymnastics, water jumps, trampoline etc.) it is necessary to perform rotational movements (crucial elements of a sports techniques), the effectiveness of which depends on a proper change in time of the athlete's angular velocity. Development of such sports disciplines and competitions is thus not only related to achievement of the right level of athlete's motor abilities, but to continuous improvement of his individual sports technique (following the accepted motor pattern).

Principles of mechanics decide about the possibility of performing a relevant number of rotations in air with certain physical capacities of competitors. It is important at which position of human body segments a subject's moment of inertia reaches the smallest value, because with this position the subject's biggest angular velocity is reached. Assuming that the external moment of a force acting on a subject equals zero, then his motion is illustrated by the principle of conservation of a moment of momentum in the equation:

$$\omega I = const \qquad (1)$$

Many researchers dealing with sport have been aware of the importance of this knowledge of mechanics for achievement of better sport performance results. They have determined the moment of inertia of the human body using adequate mathematical models [3-8]. Some of them tried to apply experimental methods, using mainly swing methods [9-12]. Another method used was the method of a rotating platform, which rotated under the action of a falling mass [13]. However, the relevant bibliography does not refer to a description of an apparatus, which, apart from determining the moment of inertia, could investigate the effect of a change in this moment on a change of angular velocity when performing a particular sports technique. An apparatus that, apart from determining the moment of inertia, could serve as a training equipment, ensuring repetition of certain motor activities in the earlier defined conditions of external forces affecting the athlete's body.

The aim of the present paper is to recommend the rotating training simulator [14,15] as an apparatus that can exercise three functions: determining the moment of inertia, improving motor habits while performing certain "rotation techniques" in various sports disciplines, simulating the effect of the external force as the cause of losing balance and falling by a man who originally was immobile (standing, sitting, kneeling, etc).

MECHANICAL DESIGN AND PRINCIPLE OF OPERATION OF THE ROTATION TRAINING SIMULATOR

The mechanical components of the rotation training simulator include an induction three-phase motor driving through a pinion-crown coupling and an electromagnetic clutch, a rotating platform /1/, as well as a programmable logic controller PLC controlling angular velocity of the rotating platform by means of an inverter (Figure 1). Apart from these elements, the rotation training simulator also includes an encoder for measuring the angle of rotation of the rotating platform connected to the input of the programmable logic controller PLC. The encoder is driven by the simulator rotation shaft giving 50 electric impulses per one rotation. The simulator is also equipped with a tension rod /2/, one end of which is fastened to the bearing plate/pulley wheel of the rotating platform and its other end has a mass /3/ fixed. The falling mass, at the moment of switching the limit switch /4/ on, transmits the signal to the input of the programmable logic controller PLC. This controller has a serial interface connector RS232 to connect with a computer recording the results of measurements and saving them in the archive file. The measurement results are also shown on a display /5/ on the operating panel. The rotation simulator is also provided with replaceable additional platforms fixed to the rotating platform and vertical bars (Figure 2, 3). The bars are fastened to the threaded holes in the turntable and the horizontal bar is fixed to holder that attaches the simulator to the room ceiling.

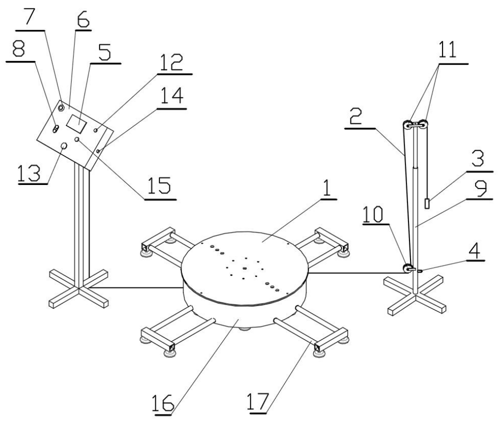


Figure 1. Diagram of the training rotation training simulator including a stand for calculating the moment of inertia (1 rotating platform, 2 tension rod, 3 mass, 4 limit switch, 5 display, 6 operating panel, 7 training simulator operation mode selection switch, 8 electromagnetic clutch switch, 9 stand, 10 lower disc, 11 upper disc, 12 angular velocity controller, 13 serial interface connector RS 232, 14 braking switch, 15 angular velocity controller, 16 training simulator base, 17 arm).

On the operating panel 6 there is a switch 7 for selecting a mode of operation of the training simulator. Depending on the requirements of the user, the simulator can operate in the first or second mode. The first mode is for determining the moment of inertia and the other is a training one.

THREE FUNCTIONS OF THE ROTATION TRAINING SIMULATOR

Mode for determining the moment of inertia

In the mode in which the moment of inertia is determined the motor drive of the moving parts of the simulator is switched off with the electromagnetic clutch switch /8/ and the rotating platform, can be set into motion by the action of an external force. A tension rod, namely a thin cord, is fastened with its one end to the circumference of a bearing plate/pulley wheel to which a turntable is fixed to. The tension rod /10/ goes through a lower disc rotatably fixed to the stand /9/ and the two upper discs /11/ and on the other end of the tension rod there is a mass fastened. Under the force of gravity the mass will be falling simultaneously through a tension rod causing the bearing plate/pulley wheel and at the same time the rotating platform to rotate. The lower part of the stand is provided with a limit switch, which after having been started by the falling mass transmits the signal to a programmable logic controller PLC. Time of the mass falling depends on the value of the moment of inertia of a turntable rotating, a subject or subjects sitting on it and on the other parts of the training simulator set into motion. By measuring the time that passed from setting the turntable in motion by a falling mass by means of the tension rod of the bearing plate to switching on of the limit switch and knowing the moment of inertia of the moving parts of the training simulator with no subjects sitting on the rotating platform one can calculate the moment of inertia that subjects sitting on the training simulator have in a particular position. The moment of inertia I_p of a subject sitting on the simulator can be estimated by means of the equation that has also been applied by Griffiths and his co-researchers [13]:

$$I_p = \frac{rtm(g - \frac{2s}{t^2})}{\omega_{final}} - I_s \qquad (2)$$

where:

I_p – the moment of inertia of the movable parts of the simulator,

r – the radius of the bearing plate/pulley wheel the tension rod is wound around,

t – time at which a mass fell the distance s,

g – acceleration of gravity,

s – distance fallen by a falling mass in t time; it is equal to the distance of the starting location of the mass at an upper part of the stand and the location of the limit switch;

ω_{final} – the final angular velocity of the bearing plate/pulley wheel after the time t; this velocity is calculated after measuring the time in the programmable logic controller PLC from the moment the mass was released, which is detected by the encoder, until a signal is transmitted to the programmable logic controller PLC 23 by a limit switch started by a falling mass.

First, the moment of inertia of the movable training simulator parts I_s with no subject sitting on it should be evaluated. It is performed similarly as before by setting the movable parts of the apparatus into motion by releasing the mass. The simulator is equipped with several replaceable masses and the distance fallen by the mass can be adjusted by changing the height of the stand. This makes it possible to select the time of the fall in order to increase the accuracy of the moment of inertia measurement with various weights of subjects and various body positions on the turntable.

Improving motor habits (the so called training mode)

When the training simulator is in the so called training mode, the stand, the tension rod and the mass are unnecessary. The motor is controlled through the inverter with a programmable logic controller PLC, which drives the turntable (with the electromagnetic clutch switched on). When the turntable reaches the desired angular velocity /12/ selected with the angular velocity controller, 12 the drive of the turntable is switched off with the electromagnetic clutch switch. By changing the distance of the subject's or subjects' body segments from the axis of rotation of the turntable, the changes of the subjects' angular velocities are recorded by means of the programmable logic controller PLC. These changes are related to motor functions that occur when practicing a particular technique of rotation. By connecting the computer PC to the serial interface connector RS232 /13/ it is possible to read out the results of angular velocity measurements recorded by the programmable logic controller PLC. The results obtained are also shown on the display on the operating panel. The results obtained are also affected by friction occurring during a rotary motion. Its value can be lowered by seating the rotation shaft of the training simulator in rolling bearings in the training simulator base as well as in the holder fixing the simulator to the room ceiling in case of using vertical bars. The course of exercises performed on the training simulator can be recorded by a video equipment shown in the figure in order to define the effect of a change in a subject's body posture (position) on his angular velocity when performing a certain rotary technique. The video camera can rotate along with the cross bar fastened to the holder fixing the training simulator to the room ceiling or it can be placed on a tripod near the training simulator. The rotary motion of the cross bar along with the turntable of the training simulator is possible by placing the rolling bearing in the holder. On the grounds of the time record when video recording and by recording the changes in angular velocity recorded by the computer PC transmitted to the logic controller PLC in the training simulator it is possible to analyze the effect of the positions of body segments of subjects performing "rotary techniques" on the angular velocity obtained.

Examples of using the training simulator for teaching "rotary techniques"

When the training simulator is operating in the second (training mode) mode the subjects, in order to increase their safety, can put on a safety harness (Figure 3). The harness can be fastened to the cross bar or to other parts of the training simulator, for example to vertical bars. Apart from that, the apparatus is provided with a braking switch /14/, which causes that the programmable logic controller PLC controls the inverter in such a way that the voltage supply to the motor ceases and the motor stops abruptly. In order the subjects can bear the rotary motions in a better way, it is possible to change the direction of the turntable rotation with a rotation direction switch /15/. The rotation training simulator is provided with a base /16/ equipped with four disengageable arms /17/ that stabilize the position of the training simulator when it is operating. If, during teaching rotary techniques the subjects have to move around the turntable, the disassembled devices as shown in Figure 3 and 4 can be applied.

Example 1. Gymnastics

A subject is lying on a disc placed on two bars at a certain height (Figure 2). For this body posture (position) a special safety harness is recommended (Figure 3). This body arrangement is similar to lying on the turntable, yet then, the arrangement of backbone will be slightly different due to the shoulder girdle attaching the turntable. When exercising a subject can change his position (posture), for example from the simple to the "tucked" posture. The decrease in the human body moment of inertia results in the increase of his angular velocity. The subject can feel the effect of the changes in the distance of the body segments from the axis of rotation on the velocity obtained and learns about the reactions of his organism to these changes.

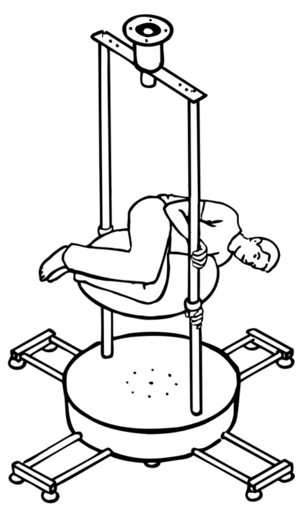


Figure 2. Using the training simulator for teaching gymnastic exercises.

Example 2. Break dance

For subjects performing head spin, there is a disc {5} lined with a soft material fastened to the centre of the turntable providing a head support for a person mastering his/her break dance techniques. Frequently, the surface friction is an unpleasant experience for those practicing head spinning. Furthermore, failing in obtaining the adequate angular velocity may result in failing to maintain the adequate posture (position) and finally in the fall. This may lead to bruises and skin abrasions of the body. Application of a movable base with safety harness can diminish the unpleasant effects of some dance elements. The training simulator can be used not only for teaching head spin but for teaching the techniques of backspin. Then, the turntable itself, without the bars and the head support disc, is enough for teaching.

When performing rotary techniques it is important to get the sense of balance accustomed to the changes in angular velocity in the rotational motion and the related acceleration that affects the body. Film ("rotating training simulator" – tutorial video is available at the website of the journal Archives of Budo Science of Martial Arts and Extreme Sports in the left menu section: *ArchBudo Sci Martial Art Extreme Sport Academy* or accessible by direct link http://www.smaes.archbudo.com/text.php?ids=101081) shows application of the training simulator for getting athletes accustomed to the changes in angular velocity as a result of changes in body posture (position) during a rotational movement. The exercising person changes his body posture from the lying to the sitting position. First, he is driven by an electric engine to reach the selected angular velocity when the engine drive is switched off. The turntable is only affected by frictional forces, if we assume that their value is zero, then the subject together with the rotating parts of the simulator complies with the law of conservation of the momentum shown in the formula 1. The changes of angular velocity affecting the subject will be the bigger the smaller the moment of inertia of the rotating elements of the rotation training simulator is. A change of the angular velocity of the rotating system of masses is effectuated by a change in the subject's moment of inertia.

The rotation training simulator in mode 1 makes it possible to determine the moment of inertia for the measurement positions shown in film ("rotating training simulator"). Exactly in the lying position (posture) as in the beginning of the experiment for the horizontal axis of rotation and the lying position for the vertical axis of rotation. The moment of inertia values obtained through the application of the rotation training simulator are close to those referred to in the bibliography on teaching biomechanics [16]. The moment of inertia determined for the standing position (posture) was from 9 to 12.5 times smaller than in the lying position (posture). During the calculation of these values the centre of gravity of the subjects should be on the axis of rotation of the rotation training simulator. With the moment of inertia of rotating elements of the rotation training simulator and using the formula 1 it is possible to calculate the changes of the moment of inertia and the resulting changes in the angular velocity of the rotating system of masses. The figures obtained can be verified empirically by reading the angular velocity value on the control panel of the rotation training simulator in the training mode (film "rotating training simulator"), focusing attention on the right position of the subject's centre of gravity when exercising.

In reality, the vertical axis moment of inertia of the person head spinning (Figure 3) is the same as when standing on the feet as shown in film "rotating training simulator". Provided, however, that particular body segments have the same arrangements in both cases. The person's behaviour in film "rotating training simulator" in terms of mechanics, is often subject to the same laws as in transferring from horizontal position (posture) on the back to the standing on the head position in head spinning. However, this reasoning is only approximate, because it does not take into account the forces the dancer puts into changing his body posture. The above analysis show the possibilities of simulating changes in angular velocity a subject can be affected by when performing "rotary techniques". In this way his body can get accustomed to these processes. At the same time, applying the knowledge of biomechanics we can empirically explain what motor activities during a rotary technique affect changes in angular velocity.

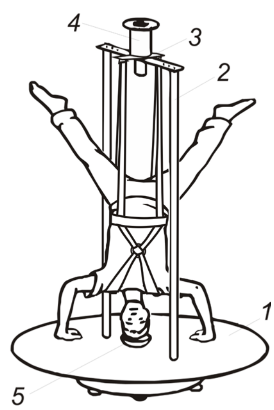
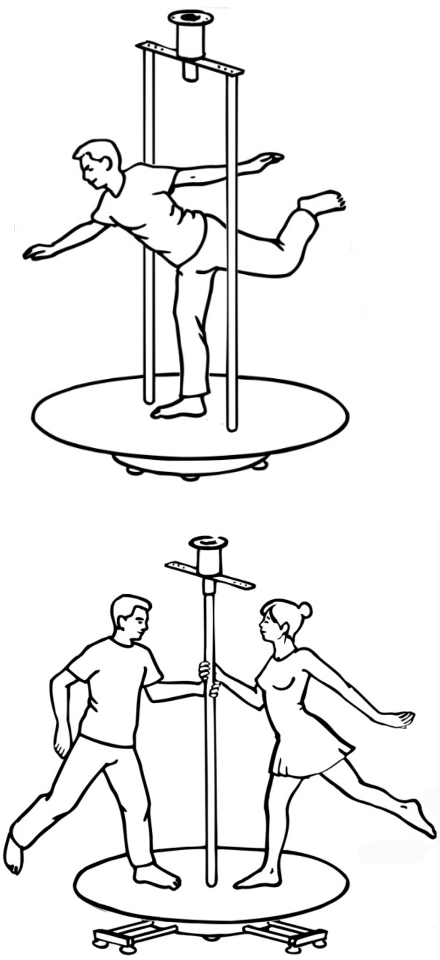


Figure 3. Using the rotation training simulator for teaching break dance (1 rotating platform, 2 two vertical bars, 3 cross bar, 4 the holder fixing the apparatus to rotating platform to the ceiling, 5 disc supporting the head).

Example 3. Figure-skating

Skaters can take up certain figures on the turntable both individually and in pairs (Figure 4). The posture assumed can copy the body posture in space when doing a pirouette. A change in positioning of particular body segments during a pirouette makes it possible to feel the relevant change in angular velocity. A skater is likely to fall when performing a pirouette in a skate rink with a high angular velocity. The subjects exercising on the rotation training simulator do not put skates on, the safety harness additionally can stabilize their body posture, thus eliminating the possibility of a fall. Changes in velocity can be big, especially for pairs of the exercising subjects. In this way, skaters, without getting into a skate rink, can learn about the reactions of their organisms to big changes in the angular velocity and for example, check their body balance sense.



(a)

(b)

Figure 4. Using the rotation training simulator for teaching figure-skating techniques
a – in individual figure-skating,
b – in pair figure-skating.

Simulation of the effect of an external force causing balance lost and a fall

It is either an individual case of the so called training mode or application of a simulation being the necessary element of supporting observations in researching methods of controlling human body affected by an external force which causes losing balance and falling of a man who originally was immobile (relative immobility – tutorial video is available at the website of the journal Archives of Budo Science of Martial Arts and Extreme Sports in the left menu section: *ArchBudo Sci Martial Art Extreme Sport Academy* or accessible by direct link http://www.smaes.archbudo.com/text.php?ids=101082). Such simulations not only refer to the situation where a person is in a car which is not moving and suddenly is hit by another vehicle (a person sitting immobile). These situations may also refer to the so called relative immobility (for example a passenger standing in a moving bus when this bus suddenly hits another object being immobile or moving). Fall simulations by means of the training simulator, with some simplifications of the reasoning, can copy external forces causing a fall of a person (hit by a running person or animal, sudden landslide, etc.). The training simulator used for training safe falls can intensify teaching effects and improve motor safety of the exercising subjects.

CONCLUSIONS

The analysed rotation training simulator can be used not only by athletes, but by circus acrobats, who practice rotational movements very often, stunts and dancers as well. Instead of fastening additional discs to two bars at a certain height, they can be fastened onto a single bar. Wearing safety harness and practicing on a single bar subjects can copy rotational figures performed by acrobats suspended from, for example, a vertical line.

Although, measurement of the moment of inertia with a turntable set in rotary motion by a falling mass can be ranked as a simple physical exercise, yet this method is regarded as an accurate one [13, 17]. Despite applying the rolling bearings, friction significantly affects the results obtained. The turntable angular velocity dependencies in the time function are linear functions. These dependencies are linear both with respect to motion as a result of a falling mass as well as the motion of the turntable after the mass fall. After the mass fall, the turntable moves in a uniformly retarded motion and stops as a result of frictional force. It is possible to make corrections of the value of the angular velocity in the formula determining the moment of inertia by using mathematical dependencies [13]. Following Griffiths et al. [13] the need to place a subject's centre of gravity on the turntable axis of rotation creates additional difficulty in obtaining accurate results.

In my opinion, the innovativeness of using the rotation training simulator mainly means mastering motor habits related to performing techniques of rotation. The advantage of this invention is also the possibility to measure and record the results of angular velocity changing during the performance of rotations, the measurement and the recoding of a subject's moment of inertia in particular positions of rotation as well as the possibility of video recording of a subject's body positions (posture) in various time sequences. Comparing the video recording of the subject's body motion with the record of angular velocity done at the same time makes it possible to analyse the correlation between the angular velocity obtained with the body posture assumed. After defining what motor activity guarantees the optimum angular velocity, a subject can practice on the training simulator his/her motor habit necessary for assuming a relevant body posture (position).

Assuming a correct body posture (being a presentation of a certain sports technique) requires an adequate level of motor abilities. This can be exemplified by break dancers who, in order to do head spin must take up a certain body posture (position). Using the rotation training simulator, standing on the head can be performed with a support provided by another person and the safety harness ensures that the subject will maintain this position (posture). The subject, assuming the right position (posture), after setting the turntable in rotary motion, can check his/her sense of balance. This experiment will prove to be useful, when a subject's level of training ensures that he is able to reach the adequate speed when dancing necessary to stand on his head and possibly continue the head spinning. The training simulator can be thus the basic tool for mastering the sense of balance in athletes that are supposed to use certain techniques requiring greater fitness. At the same time, according to the author of the present article, the sense of balance and the adequate motor habits can provide better possibilities for maintaining the right body posture (position), especially when doing ,,rotary techniques" with a great angular velocity.

When doing a rotational movement, a subject using this technique, must very often change the moment of inertia of his body which is related to changes in his/her angular velocity. When exercising on the training simulator, the mass of the rotating parts of the apparatus affects a change in the value of the subject's angular velocity which is a result of changes of his moment of inertia. Thus, it is obvious, that changes in angular velocity when practicing certain sports techniques (circus shows, etc.) in real sports competition (circus presentation etc.) do not necessarily have to be copied by those obtained on the training simulator. Therefore, the apparatus is being constantly developed in order to, not only decrease the frictional force occurring during the simulator operation, but to decrease the mass of its rotating parts.

The rotation training simulator can play a very important role in educating coaches, sports athletes, circus artists or even in the educational process of physics. It may teach to understand the effect of body positions (posture) on obtaining various values of angular velocity when performing rotations by human body. This way of explaining the rules of rotary motion mechanics in experiments can lead to, not only, understanding them quickly, but to accelerating the process of teaching motor activities qualified for "rotary techniques". Such events were proved when teaching "rotary techniques" in aikido [15, 18].

Preliminary experiments conducted by the author of the present article showed a successful application of the rotation training simulator when teaching "rotary techniques" specific for trampoline and break dance.

COMPETING INTERESTS

The authors declare that they have no competing interests.

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