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COMPUTER GAMES IN REHABILITATION OF UPPER LIMBS

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Abstract: The paper describes a research aimed at creating the low cost virtual reality based system for physical rehabilitation of upper limb. Its goal was to create a system which would assist in rehabilitation involving various kinds of limb movements. The rehabilitation simulation has an attractive form of a computer game, which should result in increase of patients' motivation thus influencing the rehabilitation efficiency. The system was designed to work at patient's home as a telerehabilitation system. For the purpose of the physical rehabilitation it was decided to use the system with two alternative display devices: HMD device (Sony HMZ-T1) and a LCD display with stereovision glasses (NVidia 3DVision). For the tracking purposes it was decided to use an inexpensive magnetic tracking game controller (Razer Hydra). Custom software with three sample rehabilitation games was created. Preliminary system assessment was performed with the participation of six patients. The system has been assessed positively by all patients and supervising therapist. Most of patients were able to relatively quickly learn the rules of each game. Performing exercises shaped in a form of games caused them pleasure.

Keywords: virtual reality, game, upper limb physical rehabilitation, Sony HMZ-T1, NVidia 3DVision, Razer Hydra

INTRODUCTION

The intensity of rehabilitation exercises is the factor of a major influence on the efficiency of physical rehabilitation [1]. A large group of patients, however, fail to perform their exercises regularly or completely discontinue the rehabilitation process [2, 3]. According to some estimates, this problem affects as many as 60-80% of patients discharged from hospital. 10% of such patients completely discontinue therapy. Insufficient motivation of patients is one of the main reasons for this fact [4]. According to some researches the virtual reality (VR) based system seems to be a good solution for this problem [5-8]. Attractive form of a computer game combined with a competition (scoring, moving to a higher level of difficulty) results in focusing patient's attention on the performed task instead of impairments. What is more, the virtual reality system can be successfully used for

home-based rehabilitation (e.g. [9, 10]). With the internet connection the rehabilitation progress can be remotely monitored by a therapist.

The paper describes a research aimed at creating the low cost virtual reality based system for physical rehabilitation of upper limb. Its goal was to create a system which would assist in rehabilitation involving various kinds of limb movements. The VR based rehabilitation simulation has an attractive form of a computer game, which should result in increase of patients' motivation thus influencing the rehabilitation efficiency. The system was designed to work at patient's home as a telerehabilitation system providing contact with a therapist and enabling remote monitoring of the rehabilitation progress.

METHODS

HARDWARE AND SOFTWARE

Using the virtual reality environment comes down to the transfer of simulated stimuli to the human senses and record his/her movements in order to allow interaction with the environment. In the simplest case, this task can be performed using a standard computer or TV monitor and devices for recording patient's movement. Such solution is simple, has low price, but also a small degree of presence in the virtual world. It also lacks of the stereovision, which is especially important when considering spatial upper limb movements. More advanced systems are based on stereoscopic projection. Image is displayed on the monitor (or screen with projectors), use of special glasses gives stereoscopic impression. The highest degree of realism is achieved in the so called immersive virtual reality systems, in which the person is cut off from visual and sound stimuli from the real environment. In these systems, the impression of spatial image is obtained by using a head mounted displays (HMD). Stereovision is achieved by using a small screens mounted on the device located in front of human eyes. For the purpose of the physical rehabilitation it was decided to use the system with two alternative display devices: HMD device (Sony HMZ-T1) and a LCD display with stereovision glasses (NVidia 3DVision).

The most important component of the rehabilitation system is the motion tracking device. It allows to record patient movements, which is crucial for rehabilitation purposes as well as for interaction with the virtual environment. This task can be achieved using various types of devices. On the one hand there is a large group of "professional" equipment featuring excellent capabilities, but also high price. On the other hand there are widely available game controllers, with limited capabilities when compared to "professional" devices, however inexpensive. For the physical rehabilitation purposes there is no need for extremely precise recording of the whole body movement, however the low price is quite desirable. One of the most interesting game controller is Microsoft Kinect

controller. It is a markerless optical tracking system and as such it is relatively easy to use. It provides tracking of the full body motion basing of the camera image. It can be successfully used in various aspects of the physical rehabilitation [11, 12]. Its accuracy is however too limited for rehabilitation exercises involving precise hand movements. Another game controller often considered as a tracking device for the physical rehabilitation is Nintendo Wii Remote controller (Wiimote) [13, 14]. It is a wireless, inertial device with limited capabilities of optical system. It can provide only limited information on rotation and position of sensor, thus it is not directly suited to track spatial movements of upper limb.

In the described research it was decided to use an inexpensive magnetic tracking system Razer Hydra (Fig. 1). It consists of central antenna and two corded pads equipped with 7 buttons and a joystick. The system can track 6 DOF movement of each pad. The main advantage of Razer Hydra controller is that as a magnetic system it provides direct 6 DOF recording of sensor movements. This is much more problematic in case of a Kinect controller and is not directly possible in case of inertial controllers, such as a Wiimote. The Hydra controller is also free of problems with skeleton recognition when limbs are close to human body, which is typical for the Kinect. What is more, it offers better accuracy than the Kinect and requires less space for proper operation. There are also drawbacks of the Hydra controller. Its useful range is limited to around 1.2 m around the central antenna. However, if the antenna is placed properly, it covers the whole range of upper limb movement. Another problem is that both pads of the controller are connected with a cable with the central antenna. In case of fast movements it may be necessary to hold these cables with rubber straps to prevent tangling. In the described research both pads of the Razer Hydra were used to capture patient's upper extremity motion. The first pad was held in his/her hand, the second one was fixed to his/her chest with a suspenders. This way it was possible to record hand movements relatively to the chest.

FIGURE 1. Razer Hydra game controller.

The custom software was created for the purpose of described system. This ensures that the system is well tailored to the physical rehabilitation purposes. The software was created on the basis of open source libraries, minimizing the total cost of the system [15]. The system provides a module for preparing the rehabilitation

program, thus allowing the therapist to choose a rehabilitation game and set such parameters as the desired range of movement and exercise duration. All important data describing performed exercises and the rehabilitation progress are stored and may be accessed remotely through the internet. For the video communication between therapist and patient Skype software is used.

REHABILITATION GAMES

For testing purpose three sample rehabilitation games have been created. The goal of the first game (Fig. 2, top) is performing wide range movements of the whole upper extremity. Patient's hand is represented as a hand avatar. During the game-play small objects – apples - appears in various places of the reach area. Patient's task is to reach each apple. In case of success another apple appears in different place. The main goal is to reach as many apples as possible in predefined time period. Position of apples is defined by the therapist.

The goal of the second game (Fig. 2, center) is to perform pronation/supination movements. Movement of patient's hand is represented as movement of a fish (manta ray).

FIGURE 2. Screens of the rehabilitation games.

During the game-play the fish swims between obstacles in a form of gates. Patient's task is to rotate the fish by performing pronation/supination movements to swim through each gate without touching it. Rotation of gates is defined by the therapist. The goal of the third game (Fig. 2, bottom) is to perform precise

movements of hand in various places of the reach area. Patient's hand is represented as a key. Small boxes with a key hole appears in various places of the reach area. Patient's task is to insert the key in each key hole and perform rotation to unlock the box. Position and rotation of boxes is defined by the therapist.

Before these games can be used by the patient all parameters must be set by the therapist. In the beginning therapist decides which games will be used, in which order and for how long. Then he/she defines described above parameters. This can be done in an intuitive way: location or rotation of objects is set using controller's pad – the therapists moves hand holding the pad to designated position and presses a keys. During the game-play the data describing performed exercises and achieved range of movement are stored and may be accessed by the therapist.

THE STUDY

Preliminary system test were performed with the participation of six patients aged 24 – 74. They were asked to use the system in each of following setups:
- configuration with the HMD device,
- configuration with the LCD screen and the stereoscopic glasses,
- configuration with the LCD screen, without stereoscopic capabilities.

All patients spent some time playing in each of the three games in all three configurations. After that patients were asked to fill a questionnaire which goal was to assess following aspects of the rehabilitation system:
- the ease of use of all three hardware configurations,
- the stereoscopic impressions including the sense of depth,
- each of three games in terms of usability, clarity and possibility to perform exercises.

Each patient was also asked to indicate the hardware configuration he/she preferred. During the study the system was also assessed by supervising therapist.

RESULTS

During the tests there were no problems with the Razer Hydra controller. Cables connecting pads with the central antenna caused no problems, there was no need to fix them to patient's extremity in any case. In the same time all of patients had problems with the Sony HMZ-T1 HMD device. They complained about the comfort of use, some of them were not able to set it correctly by themselves. According to the results of the questionnaire, the average rating was high or very high in case of all hardware configurations. In terms of convenience decidedly below has been assessed the interface with the HMD device. This is due to described above problems with its setting on the head and comfort of use. In the same time the possibility of assessing the distance was highest in the case of a HMD and the lowest in the configuration with the monitor only. All three games

were assessed positively. Especially appreciated was the simplicity of the interface of all three games. However some minor problems in software usability were spotted. Four of six persons would prefer to perform exercises using the system than in the traditional way. The remaining two persons, aged 59 and 73, had problems with immersing in the virtual environment. They did not achieved stereovision and had problems with performing game tasks.

CONCLUSION

The system has been assessed positively by all patients and supervising therapist. Most of patients were able to relatively quickly learn the rules of each game. Performing exercises shaped in a form of games caused them pleasure. However VR based rehabilitation system will not be suitable for all patients. Some of them may have problems with it and prefer traditional way of performing exercises. The overall assessment of the software was positive. Spotted problems will be used to improve the system in the next release. Hardware was also assessed positively, however some major problems with the HMD device were spotted. For the future research different HMD device must be used. Fortunately, there are alternatives available on the market: next releases of the Sony device, as well as competitive products.

In the next stage of research a study is planned aimed at assessing rehabilitation efficiency when using the VR based rehabilitation system as compared to traditional methods.

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DIFFERENCES IN THE BIOELECTRICAL ACTIVITY OF THE MAJOR MUSCLE GROUPS OF THE LOWER LIMB USING ROAD OR TRIATHLON POSITION

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Abstract: The use of different bike frame geometry in triathlon can result in change of flexion-extension angle and torque at the hip. This results in change of muscle activity involved in the bike's drive. The aim of this study was to examine the differences between the profile of muscle activity while driving on the cycle ergometer in ROAD and the profile for aerodynamic (TRI) position used in the Ironman competition for selected muscles of the lower limb.

Three men and two women of different training experience took part in the experiment. They performed cycling movement for a given power, selected individually to the intensity of the 70.3 (Half Ironman) competition and monitored by a POWER TAP hub. Recording of EMG signals was acquired from eight muscle groups of the lower limb during cycling.

Our measurements showed no significant difference between the profiles of muscle activity during pedaling in two of the studied positions. Averaged total value of bioelectrical activity of all studied muscles was higher for TRI position except the pulling phase, where the values were equal. In the pushing phase working muscles showed greater activity in the TRI position. The minimum values of the muscle activity profile were on a slightly lower level for TRI position and the periods of their occurrence differed only slightly.

Keywords: bike fit, road bike, triathlon, electromyography, muscles, lower limbs

INTRODUCTION

Triathlon is one of the fastest gaining in popularity sports in the world [1]. The nature of triathlon (IM type) is to compete sequentially in swimming (3,86 km or 2,4 mile in distance), cycling (180,2 km / 112 mile) and running (marathon 42,195 km / 26,2 mil). The longest in distance and time, therefore, the most crucial, is cycling and running phases.

Performance in cycling and running is strongly correlated with the finish time in the Olympic distance triathlon (1500m swimming, 40km cycling, 10km running) [2] and the effective transitions between these disciplines is considered as one of the keys for a better results [3]. Additionally, many injuries in triathlon are related

to cycle or running transition. Triathletes often notice that cycling impairs their running performances. To solve this issue they practice cycle/run transition to adapt their body to change biomechanical movement pattern in a very short time. These are confirmed by literature which investigates the effects of a prolonged cycling on further running. It is reported that cycling phase affects the running performance while the effects of swimming on cycling and running performance are rather small. Studies have shown that greater seat tube angle shortens the cycling and running phase [4]. This study also showed that at intensity 70% Vo2max triathletes achieved 40km distance faster (more than 1 minute) while using higher seat post angle of 81 deg then using seat post of 71 deg. Even greater diffrences were achieved for the 10 km distance run followed by cycling where the time was greater then 5 minutes.

The difference in results can be explained by both physiological and biomechanical factors. The activation patterns in the lower limb muscles were altered during the run proceeded by a cycling session [3,5]. The increased fatigue during the post-cycling run was also associated with altered leg kinematics [5]. Gottschall and Palmer also reported that prolonged cycling session affected running stride kinematics [6]. From physiological point of view extended submaximal cycling session seems to have negative effect on the performance level of the respiratory muscles that persisted through a following running session [7].

In order to eliminate all this negative phenomenon the triathletes began to use bikes with different frame geometry in relation to road bike. Triathletes use frames with steep seat post angles that are more vertical (from 80 to 84 deg) than that of typical road bikes (between 70 to 74 deg). The more vertical is the seat post the rider's great trochanter location is more directly above the crank axis. Thereby, hips are in a more extended position that has been proposed to facilitate pre-stretch of the gluteus maximus muscle and that improves the action of the muscle [8]. A few studies that have examined electromyography of the leg muscles during cycling with the conventional and steep seat post angle revealed an altered pattern of leg muscle. Brown et al. indicated that a more extended hip position helps cyclists to generate greater hip torque and at the same time biceps femoris activation was reduced [9]. This results are similar to the study of Ricard et al. where sit post angles from 72 to 82 deg were used during a Wingate test [10]. They received comparable power outputs while significantly less muscle activation was required when riding with 82 deg frames. A steeper seat post angle was also reported to improve power output during a 15 second cycling trial [8].

Triathlon-specific bike frames (steeper seat post angle) are becoming more popular in triatletes world. In connection to the guarantee of more efficient cycling techniques and of minimizing the unwanted effects of the cycling stage on the finishing running segment. Many of studies examined conditions that not exist in real race condition – in examples the effort was to short and too powerful

(anaerobic 15s, 30s wingate test) or the position in study was aerodynamic but the seat post angle was standard (72 degrees).

Therefore the aim of this study was to examine the differences between the muscle activity profile while riding on bike in road or aerodynamic (triathlon) position used in the Ironman (IM) competition for 8 selected muscles of the lower limb. Special attention was paid to the power (85% functional threshold power) suitable for long IM races and to the seat post angle that occur in real racing Iron Men condition.

The study included time handlebars which allows to accommodate extremely aerodynamic position and the higher seat tube angle (80-82 degrees) was also took into account.

MATERIAL AND METHOD

The study involved 5 subjects: three men and two women characterized by different training experience in various disciplines (Table 1.). The nominal power was selected individually depending on sex, body weight and training experience. All subjects participated voluntary in the experiment and signed a written consent form.

FIGURE 1. Measurement set-up. Bicycle with power measurement system is mounted in the rear hub and positioned on the cycle trainer. Telemetric EMG receiver is mounted on the subject's back.

TABLE 1. Description of test subjects considering the characteristics of the training and sport activity

Test Subject	Age (Years)	Body Weight (kG)	Body Height (cm)	Using ROAD Bike?	Using TRI Bike?	Sport's activity (intensity)	Trainee ship (Years)	Main Discipline	Left Leg length (cm)	Right Leg Length (cm)	ASIS Width (cm)	Left Knee width (cm)	Right Knee width (cm)	Nominal power [W]
1	25	52	160	YES	YES	high	3	TRI	83	83	22,5	10,5	10,5	110
2	21	70	172	NO	NO	low	0	gymnastics	90,5	90	28	10	10	120
3	25	78	179	YES	NO	low	5	-	95	95	25	10,5	10,5	185
4	20	70	182	YES	NO	moderate	4	MTB	90,5	90	23	10,5	10,5	270
5	25	82	192	YES	NO	moderate	9	MTB	101	101	28	10,5	10,5	270

In the study of the muscular activity we used TeleMyo 2400T kit for recording and analyzing EMG signal. EMG set consisted of the Noraxon 1400A - main unit for recording, TeleMyo 2400G2 telemetry receiver, wiring with preamplifiers, pocket for mounting the receiver on the back of a test subject and software for recording and analyzing data. Bipolar electrodes Noraxon Ag / AgCl were used for the registration of EMG signals. Each subject performed the exercise of an individual given power level monitored by the POWER TAP hub. The exercise intensity level was individually selected to match the 70.3 (Half Ironman) competition.

Eight (8) dominant muscles of the right lower limb were studied during cycling (Fig. 1) and selected according to modified guidelines of Ericson et al [4], ie: mm. biceps femoris, semitendinosus, vastus medialis, rectus femoris, vastus lateralis, gastrocnemius lateralis, gastrocnemius medialis, gluteus maximus.

The peak dynamic activity normalization method (pk-DYN) was used to compare EMG activity between muscles, which is believed to have moderate measurement reliability and repeatability for determining differences in activation amplitudes [11]. By normalizing to a reference EMG value collected using the same electrode configuration, factors that affect the EMG signals during the task and the reference contraction are the same and ineffective [12, 13].

The pedaling cycle (crank cycle) was assumed to begin with the position of the bicycle crank's arm at 12 o'clock. Bicycles were provided with power measurement system mounted in the rear hub and were positioned on the TACX FLOW trainer. The examination was preceded by a 5 minute warm-up (pedaling with the power of 50 Watts with the ROAD settings) in which reference measurement of EMG activity (test MVC) was made.

As pedaling cadence tends to decline with fatigue [14], its value was kept constant to minimize its possible impact on the studied muscle activity profiles. This constant value of cadence was thus not guaranteed to fit the preferred cadence of each subject [15], but was likely higher, which may have turned out beneficial [16].

The main test trial for ROAD position involved achieving twice the power of the warm-up. After that test subject was to pedal maintaining a constant power for a period of 3 minutes containing 1 minute registration. Two minutes rest period was then followed. Within this two minutes bikes were adapted to the triathlon (TRI) settings. After this change a 3 minutes test trial was followed for TRI settings.

Normalization to test maximum voluntary contraction (%test MVC) using peak dynamic activity normalization method was applied. The time variables were normalized and expressed as a percent of the crank cycle (%CC).

RESULTS

All measurements showed no significant difference between the profiles of muscle activity during pedaling in two of the studied positions.

The most active muscle for the ROAD position was vastus medialis (56 % test MVC at 23 % CC), then the medial head of the gastrocnemius (up to 52 %test MVC at 36 % CC). The most active muscle for the TRI position was vastus medialis (up to 55 % test MVC at 22 %CC) and then biceps femoris (up to 51 % test MVC at 39 %CC), Fig.2.

FIGURE 2. Muscle activity of the tested ROAD (A) and TRI (B) positions. Muscle bioelectrical activity is normalized to test MVC level (%testMVC) and time is expressed in percents of the crank cycle (%CC).

The averaged total muscle activity for the tested muscles (Fig. 3) was higher for TRI settings. The exception being the phase between 55 and 5% of the crank cycle (%CC) (practically the whole pulling phase), where the average, total muscle activity in ROAD position proved to be equal to the activity in TRI position.

In the pushing phase working muscles were more active in the TRI position - up to 36 %testMVC. The maximum activity for ROAD position was 33% testMVC and occurred about 3 %CC earlier than the maximum for TRI position. The minimum values were on a slightly lower level for TRI position and occurred slightly differently: at 77 %CC for TRI position and 74 %CC for ROAD position (Fig. 3).

FIGURE 3. Averaged total muscle activity for the tested muscles for ROAD and TRI positions. Muscle bioelectrical activity is normalized to testMVC and time is expressed in % of the crank cycle (%CC).

DISCUSSION

The aim of this study was to examine how muscle activity patterns during cycling were modified when the bike configuration was changed from road to triathlon settings. The two configurations differed mainly by the value of the seat post angle; it was designed to be larger in the triathlon case to help the competitors retain more energy when finishing the cycling stage of the race and passing on to the run.

Taking into account scarcity of research on the subject and the fact that situations studied so far were often far from reality, we decided to design and carry

out a study that would look at muscle activity patterns using individual exercise intensity levels quantified by mechanical power. Biomechanical and electromyographic characteristics of muscles spanning the main joints of the lower limb were examined in both bike configurations, and a dynamic method was used to normalize the signals.

Our research hypothesis concerned possible changes in timing and amount of activity of individual muscles when changing between these two bike configurations (TRI and ROAD). It originated from the belief that a change in bike configuration would cause the joint angles to change and thus lead to corresponding modifications of activity levels of the engaged muscles.

Our research showed no significant differences in muscular activity levels between the two settings. In particular, we noticed no reduction of activity levels of the biceps femoris muscle when passing to the TRI position, which corroborates the observation by Ricard et al. [6]. However, the change of position, which took place in the anterior-posterior direction, resulted in some changes in kinematics. The position of the subjects was influenced by the value of the seat post angle ranging from 70 degrees in the ROAD configuration to 82 degrees in the TRI configuration. Theoretically, that should cause a reduction of hip flexion, but in fact no significant changes of the corresponding maximum and minimum angles were noticed, even in the pushing phase. The reason for this finding may be that the more horizontal body position in the TRI configuration may have resulted in a pelvic tilt and thus led to cancelling the results of reduced hip flexion. Accordingly, corresponding changes in movement kinematics turned out to be nonsignificant.

To conclude the research:

1. Muscular activity profiles were different between TRI and ROAD settings but the difference was insignificant compared to studies by other authors.
2. Averaged total, muscle bioelectrical activity (of all involved muscles) was higher for TRI settings which was unexpected. Only the muscle activity in pulling phase was the same for TRI and ROAD settings.
3. The activity of gluteus maximus was greater in TRI settings which is consistent with the feelings of the triathlon competitors.
4. In the first pushing (or power production) phase the muscle activity was insignificantly higher for TRI seetings.

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BIOMECHANICAL ASPECTS OF LOCOMOTION DURING PREGNANCY IN TERMS OF FROUDE NUMBER

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Abstract Pregnancy is associated with anatomical and physiological changes that are a consequence of the progressive weight gain. The aim of the study was to identify gait kinematics of pregnant women and compare it with the results provided by the same group before pregnancy and six months after delivery. Kinematic gait variables were registered with a 5 camera video based system at 120 Hz (Vicon 250). The inclusion criteria aimed at selecting only healthy women planning a child in a near future walking at the same Froude number (0.2-0.3). The spatio-temporal parameters, base of support (measured as the distance between the ankles as well as between the fifth metatarso-phalangeal joints during the double support phase) and the thoracic amplitudes calculated as the absolute angular difference from maximal to minimal value within one stride cycle in sagittal, frontal and tranverse plane were analyzed. Each woman participated in 3 sessions: before pregnancy (**PRE**); during the last trimester of pregnancy (on average, after 33 week of gestation) (**IN**); half year post partum (**POST**). No significant differences were found between the pregnant and non-pregnant conditions in terms of time-space parameters. During pregnancy, both measures of the base of support increased. Consequently, the enlargement of the supporting area was followed by the larger side to side oscillations of the thorax in the frontal plane.

Keywords: kinematics, pregnancy, thorax, base of support, stability

INTRODUCTION

Pregnancy is associated with a number of anatomical and physiological alterations that are a consequence of the progressive weight gain. Majority of the changes are observed within the pelvis and lower part of the spine and these are our natural adjustments following from evolution of hominin bipedality to improve the reproductive capability of modern females (Whitcome et al. 2007). Such functional adaptation to the fetus developing in the womb is associated with laxity in

ligamentous that is likely to be caused by hormonal changes (Schauberger et al. 1996, Conti et al. 2003). Relaxin, a polypeptide hormone that regulates collagen, remodels connective tissue around the pelvis (Goldshmidt et al. 1995), as well as peripheral joints (Block et al. 1985, Huang et al. 2002). When the joint laxity increases, consequently, there is an increase in the joints amplitude (Calguneri et al. 1982, Block et al. 1985). According to some investigators the increased level of relaxin might persist until 6 months postpartum (Polden and Mantle, 1993).

However, the literature relating to altered conditions due to pregnant state is indecisive. Thus, in the expectant mothers we can observe changes both in body posture (Goldsmith et al. 1995, Jensen et al. 1996, Franklin et al. 1998), as well as in the way of forward body transfer (Huang et al. 2002, Aguiar et al. 2011). The investigators highlight the existence of different postural responses in women during pregnancy. However, these works have some limitations. Some differences in postural adaptations to pregnancy may indeed stem from individual strategy taken by women (Wu et al. 2004), but also the inconsistency in the data may follow from different methodology. In most reports we can find a comparison of walking with the natural self-selected speed in pregnant and non pregnant conditions (Gilleard 2013, Wu et al. 2004). However, the use of natural velocity may contribute to the variability of biomechanical parameters reported since it determines the whole range of variables characterizing the walking pattern. But we are aware that this parameter may have different values as it is affected by the body size. Kramer and Sarton-Miller (2008) noted that people can differ substantially in leg length affecting self-selected walking velocity and VO_2 therefore energy efficiency variables may be affected. The principle of dynamic similarity states that geometrically similar bodies that rely on pendulum-like mechanics of movement, have similar gait dynamics at the same Froude number (Alexander 1989, Vaughan and O'Malley 2005, Leurs et al. 2011). That is why we decided to engage in our study such dimensionless parameter to provide comparable inclusion criteria.

Aim of the study

The aim of the study was to identify gait kinematics of pregnant women on the base of the selected parameters in comparison to the results provided by the same subjects before pregnancy and six months after the baby was born. Rigorous inclusion criteria allowed to provide a group of women walking with a similar value of the Froude number.

MATERIAL AND METHODS

Gait registration was carried out in the Biomechanics Department at University School of Physical Education in Krakow in 2009 - 2012. The preliminary inclusion criteria aimed at selecting only healthy women, planning a child in a near future.

Subjects with neurological and orthopedic problems were excluded. As a result, our criteria fulfilled 21 women. Each woman participated in 3 sessions:

- first: before pregnancy (**PRE** pregnancy state);
- second: during the last trimester of pregnancy (on average, after 33 week of gestation) (**IN** pregnancy state);
- third: half year after delivery (**POST** pregnancy state).

Gait parameters were derived from a 3D motion capture system (Vicon 250, Oxford Metrics Limited, Oxford, United Kingdom). As described for the Golem model (Vicon 512 Software Manual), 25-mm diameter reflective markers were placed over the standard anatomical landmarks: 4 on the head, 4 on the trunk, 3 on the pelvis and 7 on each of the upper and lower limbs. Since trunk was of our special interest, the markers defining this segment were located on the spinous process on the 7th cervical vertebra (C7), the spinous process of the 10th thoracic vertebra (T10), centrally, on the collarbone (or clavicle) just below the throat (CLAV), and on the lower end of the breast bone (STRN).

TABLE 1. Average values of the selected morphological parameters in all groups of women (*mean±standard deviation*): **PRE**, **IN**, **POST** – state of women in terms of pregnancy, **BMI** – Body Mass Index (ratio of body mass [kg] per body height [m^2], **Inter-ASIS** – distance between left and right Anterior Superior Iliac Spines;

Pregnancy state	Height [m]	Body mass [kg]	BMI [kg*m^{-2}]	Inter-ASIS [cm]
PRE	1.68±0.06	58.07±6.78	20.64±3.12	23.93±1.74
IN	1.68±0.06	69.50±7.07	24.62±3.67	26.40±3.23
POST	1.68±0.06	60.07±8.13	21.09±2.80	24.15±1.98

After the calibration of the measuring system, the women were asked to walk with bare feet at their own pace across the room on the ground covered with a special non-slip surface. They were wearing tight-fitting shorts and t-shirt. After gait registration, the measurement of appropriate anthropometric parameters was performed that enabled the Vicon software mathematical processing of the data. Then gait parameters were analyzed for both physiological states to identify potential changes. The study protocol was approved by the Bioethics Committee and informed consent was obtained from all subjects. The observation of changes in the structure of the females' body in different physiological states (pregnancy vs. non pregnant conditions) are presented in table 1.

After data collection, the preferred walking speed for each trial of the given subject was determined from about 10 gait cycles. However, considering different

sizes of our individuals, we took into account the theory of dynamic similarity (Alexander 1989). According to this theory two bodies behave similarly, in terms of dynamics, if they move at the same Froude (Fr) number, defined as:

$$F_r = \frac{v^2}{gl} \qquad (1)$$

Where:

v is the speed of progression (m/s),

g is acceleration due to gravity (9.81 m/s^2 on Earth),

l is a leg length (m).

Since Fr of 0.25 is the dimensionless speed corresponding to walking at optimal close to the most economic speed in humans (Alexander 1989, Leurs et al. 2011), thus, our final group was composed of **11** women with **Fr** ranged from **0.2 to 0.3**. Adopting Fr = 0.25 strictly, would drastically decrease the number of our subjects.

In our work we analysed only the selected kinematic parameters characterizing locomotion of the studied women. The gait variables of interest were spatio-temporal parameters, the dimensions of the supporting base and the thoracic amplitudes calculated as the absolute angular difference from maximal to minimal value within one stride cycle in sagittal, frontal and tranverse plane.

Spatio-temporal gait parameters (SPT)

The step length was measured as the distance between two consecutive heel strikes. **The step cadency** was the number of steps per minute. **Double support time** was measured as the period during both feet were in contact with the floor during one walking cycle, corresponding to the period between the initial contact of the heel of one foot and the toe off of the contralateral foot. **Single support time** was the period when one foot was in contact with the ground during one walking cycle. Temporal variables were calculated as normalized values according to total cycle time. Ten walking cycles were analyzed for each individual at each collection time.

Measureas of the width of base of support:

BOS I – a distance between the markers placed on the right and left lateral malleolus (RANK – LANK) during double support phase measured on the base of horizontal coordinate (X) according to the laboratory coordinate system. **BOS II** - a distance between the markers placed on the fifth metatarso-phalangeal joint of the right and left foot (RMT5-LMT5). We believe that this measurement more accurately reflect functional BOS during gait considering the feet positioning on the ground. **NBOS** (normalised base of support) calculated according the following formula:

$$NBOS = \frac{BOSI}{Inter - ASIS} \qquad (2)$$

This ratio is useful in our measurements because of the relationship between the functional aspect of the movement system (foot positioning), and its morphological aspec`t (pelvic width).

RESULTS

The spatio-temporal results are presented in table 2. No significant differences were found between the pregnant and non-pregnant conditions. Thus: gait velocity, step cadence, step length, double and single support time during pregnancy were similar to those measured before gestation and half year post partum.

TABLE 2. Spatio-temporal parameters of gait (*mean±standard deviation*): **PRE**, **IN**, **POST** – state of women in terms of pregnancy, velocity (**V**), step cadence (**SC**), step length (**SL**), double support (**DS**) and single support time (**SS**)

Pregnancy state	V [m/s]	S.C. [step/min]	SL [m]	DS [s]	SS [s]
PRE	1.60±0.08	122.4±8.65	0.78±0.03	0.20±0.02	0.40 ±0.03
IN	1.62±0.07	124.7±7.14	0.78±0.07	0,19±0,01	0.39±0.02
POST	1.64±0.09	126.0±5.20	0.78±0.04	0.19±0.02	0.39±0.02

TABLE 3. Measures of the base of support (**BOS I, BOS II** and **NBOS**) (*mean±standard deviation*) during the double support phase in gait of women before pregnancy (**PRE**), in gestation (**IN**) and after delivery (**POST**)

Pregnancy state	BOS I [mm]	BOS II [mm]	NBOS
PRE	141±25	178±29	0.68±0.12
IN	161±24	195±32	0.69±0.09
POST	158±22	187±31	0.69±0.09

As our analysis revealed, the sizes of the base of support registered in three periods differed among themselves (table 3). Thus we observed the effect of gestation: BOS I before pregnancy (on average, 141 mm) was smaller than that

observed in gravid conditions (161 mm) or after giving birth to a child (158 mm). Similar trend was registered in the distance between the fifth metatarso-phalangeal joint of the right and left foot (BOS II), where the mean value was larger during pregnancy than half year post delivery (195 mm and 187 mm, respectively). However, the overall observation of the dimensions of the supporting area registered post partum is a natural tendency to reach the values close to that of pre-pregnancy time.

Considering NBOS as the ratio of the width of supporting base (BOS I) to the width of the pelvis (inter-ASIS distance) it remained constant (0.68 before pregnancy; 0.69 in gravid women and post partum).

The thorax angle is a global angle relative to anatomic axes (Vicon 512 Software Manual). According to the obtained data, all the stages of our research were accompanied by similar movement amplitudes performed by this segment in the sagittal plane (about 3 deg).

FIGURE 1. The thoracic range of motion (ThROM) in sagittal, frontal and tranverse plane during gait of women before pregnancy (PRE), during gestation (IN) and after delivery (POST).

Some differences, however, were recorded in the thorax obliquity in the frontal plane in gravidas. Observing the data we can see larger side-to side oscillations (by 2 deg) comparing to the state before and after pregnancy (about 4 deg). Also thoracic mobility in the transverse plane was affected by gestation. Then, in gravid females, we noticed reduced rotations by around 3 deg as compare to the resting

situations. Generally, as to the values registered in POST state, it is worth of mentioning, that there was a tendency to reach the level close to PRE period.

DISCUSSION

Pregnancy is a physiological state that triggers the natural adaptive mechanisms within the women's body to provide proper conditions for the child. In the expectant mother there are many changes affecting the musculoskeletal system, which in turn may lead to changes in the posture and the mode of walking (Huang et al. 2002, Carpes et al. 2008, Forczek and Staszkiewicz 2012).

One of the most variable morphological parameters in gravid female is body mass. Its growth is associated with an increase of the pregnant tissues but mainly with growing and developing fetus. In the present study, body weight recorded for women in advanced pregnancy reached about 70 kg which was about 11 kg more than before gestation. This is usually recognized as a mean body mass increase in the literature (Jensen et al. 1996, Foti et al. 2000, Opala-Berdzik et al. 2010). We additionally assessed women's body proportions using BMI, the commonly known ratio of the body weight (kg) to the square of body height (m²). We observed higher values of this parameter in gestation (24.6 $kg*m^{-2}$) than in two other measurement sessions. As postural characteristics of overweight and obese women is different than in females with normal weight, that is why our inclusion criteria aimed at selecting women with BMI below the 24.9 $kg*m^{-2}$, which is the upper limit of normal BMI set by the World Health Organization (Hergenroeder et al. 2011).

Many scientists emphasize the effect of anthropometry on the quantitative aspect of movement (Alexander 1989, Leurs et al. 2011). Hence in their studies, the Froude number is used to differentiate between the effects of walking velocity and body dimensions. Our analysis of the selected spatio-temporal parameters of locomotion showed that the determination of walking speeds using Froude number was a successful method to establish dynamic walking similarities between subjects of different body sizes. Thus, the basic kinematic variables: step frequency, step length, single and double support time, recorded in consecutive research stages were similar. Meanwhile, according to the literature, gravidas usually used to reduce their length and frequency of step that results in a slight decrease in walking speed (Wu et al. 2004, Carpes et al. 2008). Simultaneously, Aguiar et al. (2011) noticed a slight increase in walking speed in women in the second trimester of pregnancy compared to non-pregnant females. In order to minimize the potential instability, pregnant women lengthen the foot contact with the ground, which extends the double support phase (Bird et al. 1999, Foti et al. 2000, Carpes et al. 2008). However we did not notice such tendency in our experiment.

Masten and Smith (1988) suggested a deterioration of the stability during gestation because of the changes in body mass as well as in overall shape of the body and shifting the center of gravity. Several researchers have investigated static standing postural stability during pregnancy (McCrory et al. 2010, Jang et al. 2008, Butler et al. 2006). Thus Butler et al. (2006) reported increased standing postural sway throughout pregnancy, as evidenced by the increased center of pressure path length. Similarly, Jang et al. (2008) found increased anterior–posterior and radial sway, but no change in medial-lateral sway. They also noticed a wider preferred stance width in pregnant women during quiet stance when compared to non-pregnant subjects. It was also recognized in the dynamic conditions: Bird et al. (1999) and Foti et al. (2000) found that step width while walking increased during pregnancy. The placement of the feet on the ground may be used to define the size of the supporting base. While Foti et al. (2000) presume that walking with a wider base of support necessitates large side to side excursions of the center of mass and is energy inefficient, the results of our other studies revealed, the percentage of mechanical energy recovery in pregnancy was similar to pre and post pregnancy states (Forczek and Ivanenko 2013). In the present study, the magnitude of the area of support was determined in two ways: BOS I was calculated as a distance between the markers located on the lateral malleolus of the right and left foot at the moment when both feet were on the ground, while BOS II was a distance between the markers placed on the fifth metatarso-phalangeal joint of the right and left foot. We could see wider placement of the feet in gravidas in both measures, but larger values were related to BOS II. It was a result of positioning the feet more laterally. The interpretation of such behavior is not so clear: either it is a response to a need for stability (Bird et al. 1999, Carpes et al. 2008), or it is just a mechanical consequence of increased pelvic width (Foti et al. 2000). The rationale for the first explanation is a prevention from a risk of falls, since in the second trimester of pregnancy scientists observed a high percentage of falls in women (Butler et al. 2006, McCrory et al. 2010) comparable to the number of falls in older people.

As to the second, we should bear in mind that the manner of the feet contact with the ground remains in close relationship with the body dimensions. Hence, we took into account the normalized base of support. It was calculated as the ratio of the supporting base to the pelvic width. It occured that NBOS remained stable in pregnant women compared to the same females who were not pregnant (0.68 before pregnancy; 0.69 in gravidas and post partum). Due to that we noticed a consequence of increasing the width of the pelvis segment due to the developing fetus and enlargement of the distance between the feet during walking. This observation also provided Foti and colleagues (2000). Since both interpretations seem to be reasonable at this moment we are not able to solve this issue unequivocally.

Consequently, the increase of the base of support was followed by the larger side to side oscillations of the thorax, that only confirmed the data of Gilleard (2013) who reported larger amplitude as the body is shifted over the weight bearing leg during pregnancy. This compensatory movements may improve the stability of locomotion. At the same time, rotational movements of this segment appeared to be reduced by 3 deg in the transverse plane if compare to the state before pregnancy and post delivery. It may be a result of the growing fetus that provided additional anterior load in the trunk. Reduced rotations of the thorax may result from a reduced stride lenght (Wu et al. 2004), or conversly (Gilleard 2013). The size of this amplitude is small and may be related to the increase of lower trunk moment inertia during pregnancy (Jensen et al. 1996). Beside, like in the study of Foti et al. (2000) or Gilleard (2013), we did not observe any changes in the thorax tilt range of motion in the sagittal plane.

COCLUSIONS

1. Pregnancy as a different physiological state, does not significantly affect the majority of the analyzed time-space gait parameters in terms of Froude number.
2. A natural consequence of changed distribution of body mass during pregnancy is smaller amplitude of the thorax movements in the transverse plane.
3. Increased width of the base of support in gravid women results in compensatory movements of the upper trunk in the frontal plane in order to improve the stability of locomotion.

RECOMMENDATIONS

Due to the changes in the female's body during pregnancy, which may result in overload of the musculo-skeletal system, the expectant mothers are recommended the specialized program of physical actvity involving both, exercises as well as the right positions while performing any activities of daily living.

Physical exercises during pregnancy, if used properly, prevent from significant alterations of body statics and maintain the appropriate joints range of motion. They should be aimed at maintaining and even increasing the elasticity of the abdominal muscles as well as stretching and unloading the paraspinal muscles of lumbo-sacral spine. The purpose of exercises is also to prevent from knee valgus and flat foot.

For women, on the third day after physiological or operative delivery, should be introduced the exercises focused on the ground sensation and to improve posture of the body.

Our future research will be focused on the examination of the effect of individually tailored training on the women's posture and pattern of gait during pregnancy and post partum.

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BIOMECHANICAL ANALSIS OF FLAT BENCH PRESSING (CASE STUDY)

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Abstract: Bench press is a basic exercise what prepares competitors participating in both individual and team sports. It is also one of sports discipline in World Championship. In this study participated twenty healthy man, however, one was selected for analysis (age, 24 yrs; height: 176 cm.; body weight:80 kg; RM in bench press: 100 kg). Fundamental purpose of the study was recognition inside and outside structure of flat bench pressing depending of the weight of loading. In the research there was activity of four muscles taken under consideration: *pectoralis major*, *anterior deltoid*, *triceps brachii* and *latissimus dorsi*. Structure of the movement of flat bench pressing depending of the weight of loading consists of: bioelectrical activity four muscles, vertical acceleration curve, vertical velocity curve, displacement curve in three planes (vertical - S_y and horizontal - S_x – parallel to the line of the shoulders; S_z – from the shoulder towards the nipples contrariwise), angular characteristics in elbow joints in a right and in a left limb, angular characteristics in humeral joints in a right and in a left limb.

Keywords: flat bench press, muscle activity, structure of the movement

INTRODUCTION

Bench press is a basic exercise what prepares competitors participating in both individual and team sports. It is also one of sports discipline in World Championship. The outcomes, what are gained by strongmen, powerlifters, bodybuilders in this competition, are essentially up to the level of motor skills acquired through the training, abilities of using them in sports technique action, involvement (understood as emotional attitude) and also, but to a lesser extent, tactics in passing out another trial.

A successful bench press lift is performed when the barbell is first lowered to the chest and then moved to a fully extended position again. The bench press is consists thus from two phases: the ascending and descending. The most important is the first one, the ascending phase (Król et al. 2010).

In the available literature there is generally a lot of information regarding the bench press. However, this applies selected aspects of the bench press. The literature include, inter alia: gripping the differences between a free weight and machine bench press (McCaw et al., 1994; Langford et al., 2007). Santana et al. (2007) measured spine and right-hand (pressing-hand) kinematics with an electromagnetic tracking instrument and electromyographic of the standing cable press and bench press. To identify the descent and ascent phases during the bench press exercise Lagally et al. (2004) place a goniometer on the lateral surface of the elbow to monitor joint flexion and extension.

Although there are many publications about bench press (Sanata et al., 2007; Floyd et al., 2009) there are few data describing how the kinematics of a lift and muscle activity change during increase the weight of the bar (Elliott et al., 1989; Drinkwater et al., 2007). Most of thesis show thus the changes of mechanical parameters during flat bench pressing, however, no response which muscles decide about their growth. Only full-phase structure of the movement covering both muscle bioelectrical activity (internal structure) and the characteristics of acceleration, velocity and displacement (outer structure) will fairly evaluate how to perform motion task.

Fundamental purpose of the study was recognition inside and outside structure of flat bench pressing depending of the weight of loading. In the research there was activity of four muscles taken under consideration: *pectoralis major*, *anterior deltoid*, *triceps brachii* and *latissimus dorsi*.

METHODS

PARTICIPANTS

In this study participated twenty healthy man, however, one was selected for analysis (age, 24 yrs; height: 176 cm.; body weight: 80 kg; RM in bench press: 100 kg). The research project was approved by the Committee of Bioethics situated in the Academy of Physical Education in Katowice.

EXERCISE PROTOCOL

Protocol included flat bench pressing with free weights and touch and go technique. Research took place in two session: warm up and main session. After a general warm-up (10 minutes run on the treadmill) each subject performed a specific warm-up that consisted of three sets of the bench press with 10 repetition at 40-60% RM.

In the main session subjects performed consecutive sets of flat bench pressing with the increasing weight of loading (about 70, 80, 90 i 100% RM the anticipated maximum weight) until the appointment of one repetition maximum (RM; Baechle

et al. 2008). Each subjects performed between six and nine sets with a five minute break.

ELECTROMYOGRAPHY

The EMG signals were measured by a Pocket EMG System (BTS Company, Italy). All active channels were the same, and the measuring range was fitted to the subject (typically +/- 10mV). The analog signal was converted into a digital one with 16 bit sampling resolution and collected on measure unit. EMG activity was recorded using surface electrodes for muscles: *pectoralis major*, *anterior deltoid*, long head of *triceps brachii* and *latissimus dorsi*. All electrodes were placed on the right side of the subjects. Pectoralis major electrodes were positioned halfway between the sternal notch and anterior axillary line, approximately 2 cm apart in-line with muscle fibers. Anterior deltoid electrodes were placed two finger-breadths below the acromio-clavicular joint and angled towards the deltoid tuberosity. The electrodes for the triceps brachii were positioned mid-way between the acromion and olecranon processes on the posterior portion of the upper arm on the long head of the triceps, approximately 2 cm apart following the muscle fibers. Latissimus dorsi electrodes were placed in the middle part at the height of spinous process the first lumbar vertebra. A ground electrode was placed directly over the right anterior-superior iliac spine. This method of electrode placement is similar to that of Cram and Kasman (1998). Using the start, midpoint, and endpoint identified from the BTS System data of each trial, the integrals of the linear envelope in mVs (IEMG; integrate after present time - 0.1 s) were calculated over the descent and ascent phases for each muscle during each trial.

DATA COLLECTION

Multidimensional movement analysis was made with the measuring system Smart-E (BTS, Italy) which consisted of six infrared cameras (120 Hz) and a wireless module to measure muscle bioelectric activity (Pocket EMG). Technical accuracy of measurement the distance between markers amount to 0,4 mm. Then we calculating the average values and standard deviations (±SD).

RESULTS

Structure of the movement of the flat bench pressing depending of the weight of loading one subject is shown in Figure 1A.B.C.D.E.F., 2A.B.C.D.E.F., 3A.B.C.D.E.F., and 4A.B.C.D.E.F. It consist of: bioelectrical activity four muscles: *pectoralis major*, *anterior deltoid*, *triceps brachii* and *latissimus dorsi* (1A-4A); vertical acceleration curve (1B-4B); vertical velocity curve(1C-4C), displacement curve in three planes (1D-4D; vertical - S_y and horizontal - S_x – parallel to the line of the shoulders; S_z – from the shoulder towards the nipples contrariwise), angular

characteristics in elbow joints in a right and in a left limb (1E-4E), and angular characteristics in shoulder joints in a right and in a left limb (1F-4F).

Integrated bioelectrical muscle activity (IEMG) shown table 1. Increasing load from 70% RM to 100% RM prompted measurable activity growth of studied muscles both in ascent and descent phase. The exception is *pectoralis major* and *triceps brachii* muscles in which in ascent phase with the loading of 100% RM decreased activity.

The symptom of muscles getting involved in bench pressing is bar kinematics what is characterized by the graph of the acceleration. It definitely changes while the weight of loading increase, but only if the bench pressing ascent phase of 70% and 80% RM reaches one positive acceleration area (region) and one negative acceleration area (Figure 1B and 2B) and in attempts 90% and 100% RM, there are two and more acceleration regions (Figure 3B and 4B). Vertical component of a bar velocity increases together with the increase of loading at average and maximum values (Figure 1C, 2C, 3C, and 4C).

TABLE 1. The descent and ascent phases average values of the integral muscle activity (IEMG): *pectoralis major*, *anterior deltoid, triceps brachii* and *latissimus dorsi* during the flat bench pressing with load 70%, 80%, 90% and 100% RM

DESCENT PHASE	Pectoralis Major (mVs)	Anterior Deltoid (mVs)	Triceps Brachii(mVs)	Latissimus Dorsi (mVs)
70% RM	0.43 ± 0.06	0.55 ± 0.27	0.11 ± 0.03	0.05 ± 0.02
80% RM	0.43 ± 0.09	0.62 ± 0.29	0.19 ± 0.07	0.06 ± 0.02
90% RM	0.52 ± 0.08	0.70 ± 0.23	0.17 ± 0.04	0.06 ± 0.02
100% RM	0.56 ± 0.12	0.71 ± 0.29	0.22 ± 0.08	0.07 ± 0.02
MEAN ±SD	0.49 ± 0.06	0.65 ± 0.06	0.17 ± 0.04	0.06 ± 0.01
70% RM	0.64 ± 0.14	0.86 ± 0.23	0.27 ± 0.12	0.06 ± 0.01
80% RM	0.58 ± 0.10	0.85 ± 0.16	0.35 ± 0.16	0.08 ± 0.02
90% RM	0.70 ± 0.11	0.92 ± 0.12	0.53 ± 0.18	0.12 ± 0.04
100% RM	0.51 ± 0.19	0.93 ± 0.09	0.44 ± 0.16	0.16 ± 0.05
MEAN ±SD	0.61 ± 0.07	0.89 ± 0.03	0.40 ± 0.10	0.11 ± 0.04

The horizontal bar displacement (S_x – parallel to the line of the shoulders; S_z – from the shoulder towards the nipples contrariwise) are larger in the descent phase than in the ascent phase (Table 2). The vertical bar displacement in the descent phase is smaller than in the ascent phase.

FIGURE 1. Structure of flat bench press with load 70% RM: A) Integrated muscles activity (IEMG): *pectoralis major, anterior deltoid, triceps brachii* and *latissimus dorsi*; B) Vertical acceleration; C) Vertical velocity; D) Displacement of the bar (vertical - S_y and horizontal - S_x – parallel to the line of the shoulders; - S_z – from the shoulder towards the nipples contrariwise); E) Angles at the elbow joints (flexion, extension) for the left and right upper limb; F) Angles at the shoulder joints (extension, flexion, and adduction, abduction).

FIGURE 2. Structure of flat bench press with load 80% RM: A) Integrated muscles activity (IEMG): *pectoralis major, anterior deltoid, triceps brachii* and *latissimus dorsi*; B) Vertical acceleration; C) Vertical velocity; D) Displacement of the bar (vertical - S$_y$ and horizontal - S$_x$ – parallel to the line of the shoulders; - S$_z$ – from the shoulder towards the nipples contrariwise); E) Angles at the elbow joints (flexion, extension) for the left and right upper limb; F) Angles at the shoulder joints (extension, flexion, and adduction, abduction).
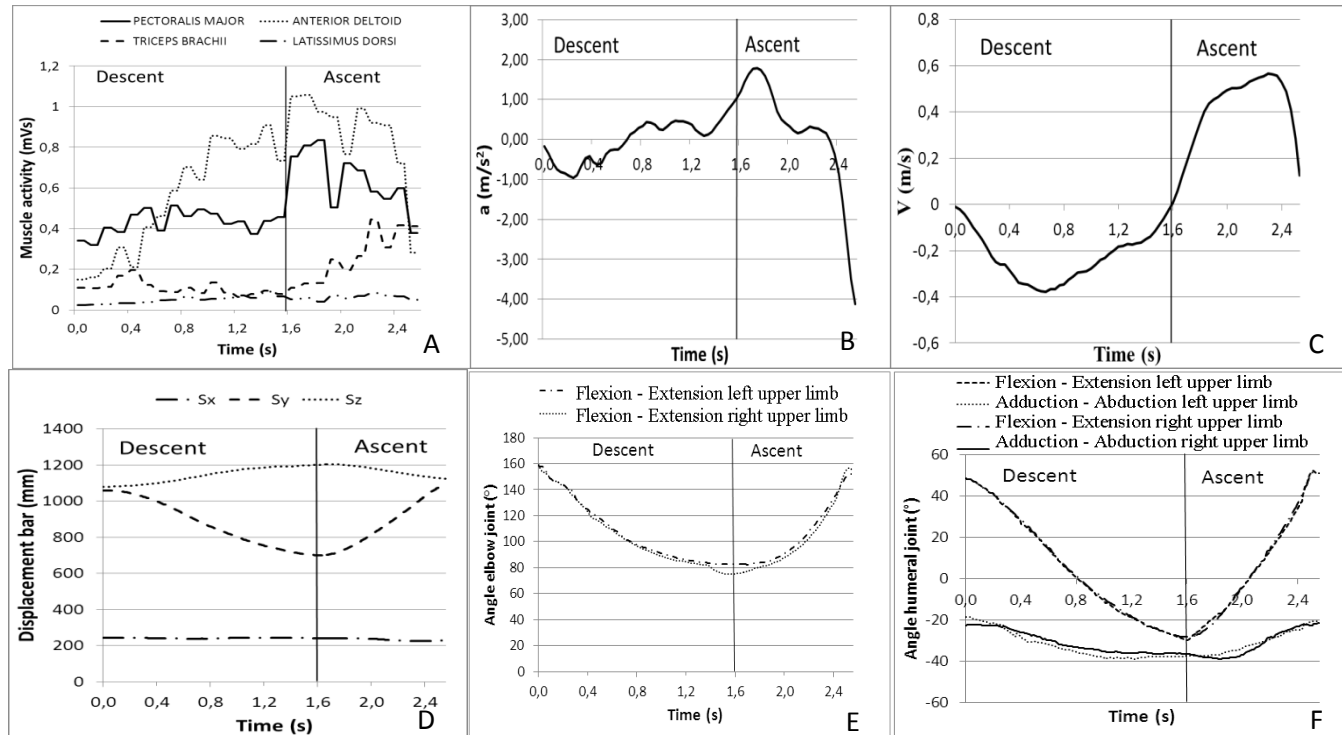
FIGURE 3. Structure of flat bench press with load 90% RM: A) Integrated muscles activity (IEMG): *pectoralis major, anterior deltoid, triceps brachii* and *latissimus dorsi*; B) Vertical acceleration; C) Vertical velocity; D) Displacement of the bar (vertical - S_y and horizontal - S_x – parallel to the line of the shoulders; - S_z – from the shoulder towards the nipples contrariwise); E) Angles at the elbow joints (flexion, extension) for the left and right upper limb; F) Angles at the shoulder joints (extension, flexion, and adduction, abduction).

FIGURE 4. Structure of flat bench press with load 100% RM: A) Integrated muscles activity (IEMG): *pectoralis major, anterior deltoid, triceps brachii* and *latissimus dorsi*; B) Vertical acceleration; C) Vertical velocity; D) Displacement of the bar (vertical - S_y and horizontal - S_x – parallel to the line of the shoulders; - S_z – from the shoulder towards the nipples contrariwise); E) Angles at the elbow joints (flexion, extension) for the left and right upper limb; F) Angles at the shoulder joints (extension, flexion, and adduction, abduction).
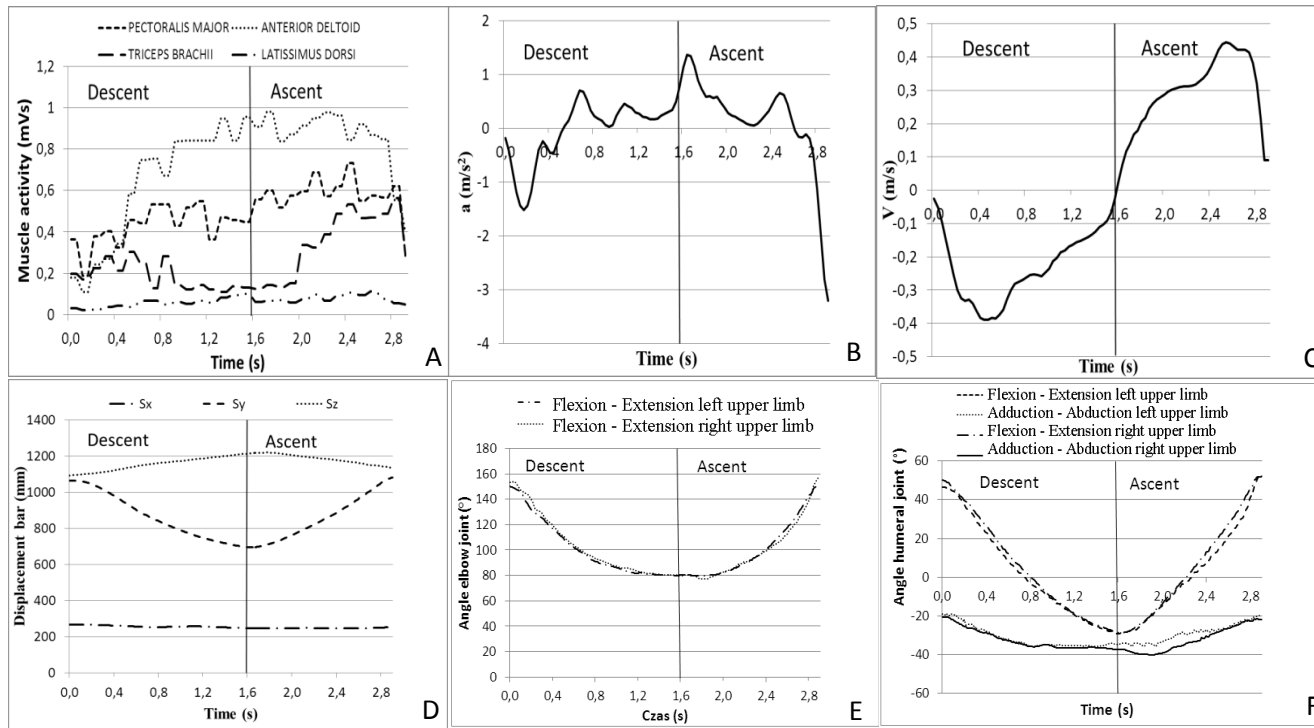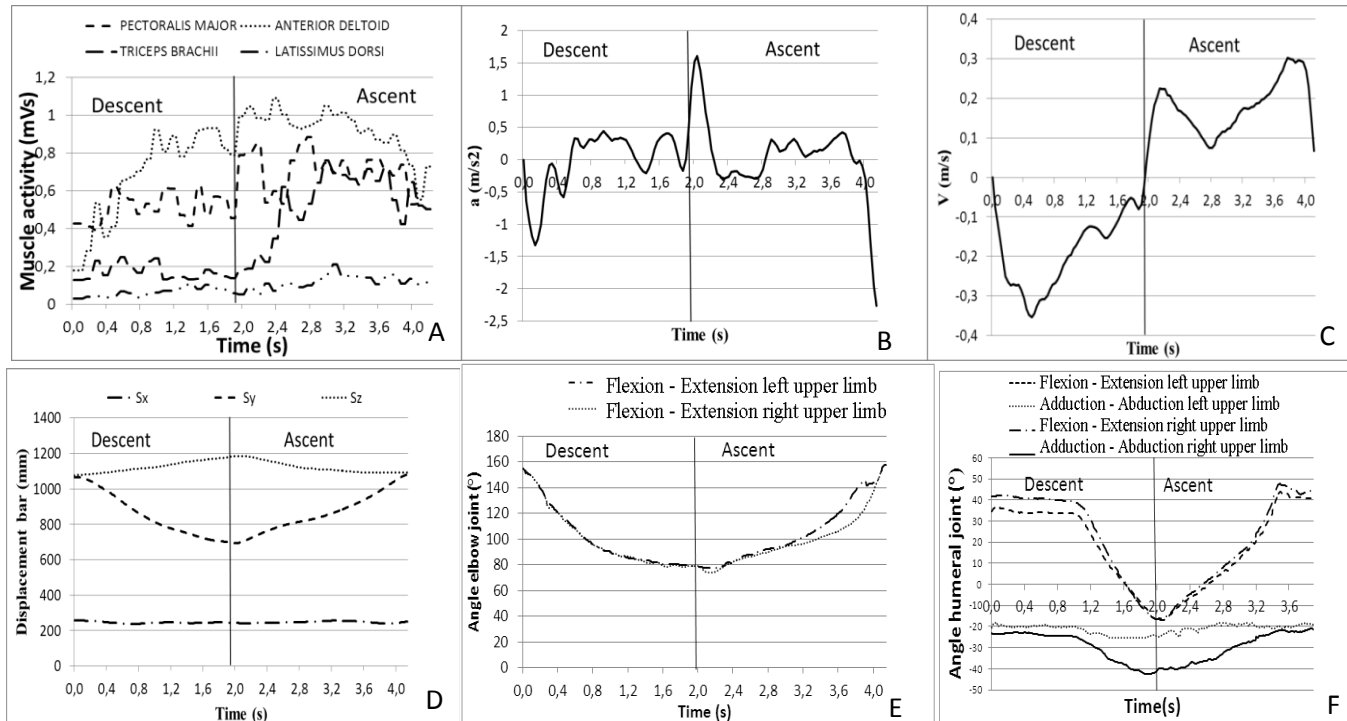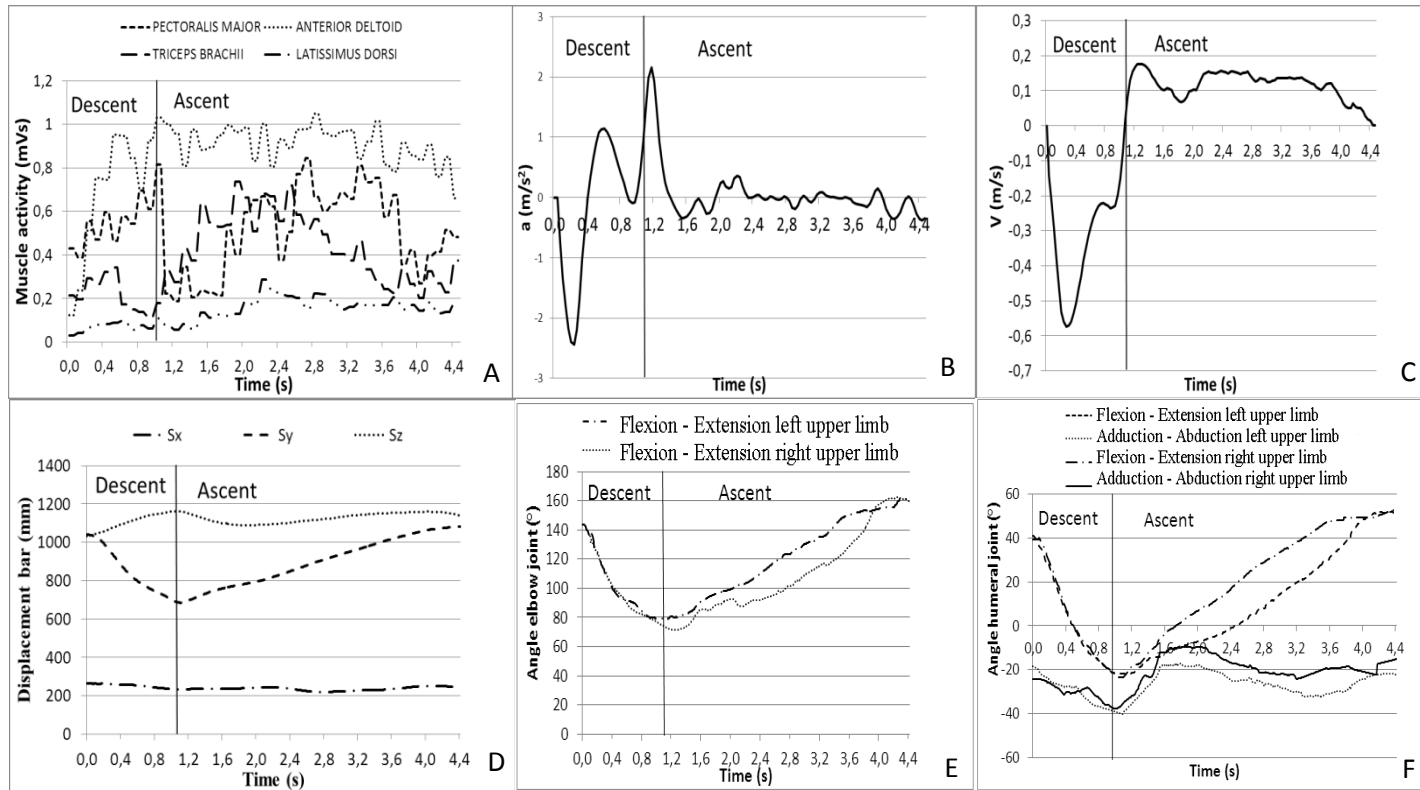
Vertical and horizontal displacement are the result of angle changes in joints of upper limbs, especially in elbow and shoulder joints. In the elbow joints in the ascent phase mean angles changes are about 5º greater than descent phase (Table 3). A similar difference was recorded for the left shoulder joint in the extension-flexion motion.

TABLE 2. Vertical (S_y) and horizontal (S_x – parallel to the line of the shoulders; S_z – from the shoulder towards the nipples contrariwise) displacement of the bar during the descent and ascent phases flat bench pressing with load 70%, 80%, 90% and 100% RM

DESCENT PHASE	S_X (mm)	S_Y (mm)	S_Z (mm)
70% 1-RM	2.3	357.2	122.2
80% 1-RM	19.2	370.5	120.9
90% 1-RM	14.2	372.3	107.3
100% 1-RM	28.7	353.2	129.2
MEAN ±SD	16.1 ± 9.5	363.3 ± 8.3	119.9 ± 7.9
ASCENT PHASE	S_X (mm)	S_Y (mm)	S_Z (mm)
70% RM	11.4	386.9	75.5
80% RM	7.0	387.0	79.9
90% RM	8.5	387.0	92.6
100% RM	12.6	396.8	22.1
MEAN ±SD	9.9 ± 2.2	389.4 ± 4.3	67.5 ± 27.0

TABLE 3. Average changes the angles at the elbow joints (flexion and extension) and the shoulder joints (extension, flexion, and adduction, abduction) for the left and right upper limb during the descent and ascent phase flat bench pressing for all studied loads (70-100% RM)

	Elbow joint		Shoulder joint			
DESCENT PHASE	flexion left limb (°)	flexion right limb (°)	extension left limb (°)	adduction left limb (°)	extension right limb (°)	adduction right limb (°)
MEAN ±SD	71.3±5.0	75.5±6.0	65.1±15.7	13.8±6.9	52.7±14.1	25.3±13.6
ASCENT PHASE	extension left limb (°)	extension right limb (°)	flexion left limb (°)	abduction left limb (°)	flexion right limb (°)	abduction right limb (°)
MEAN ±SD	75.2±5.6	80.4±3.8	70.2±16.8	13.9±5.3	55.±29.78	25.8±13.8

DISCUSSION

Analysis of the internal structure of flat bench pressing (the level and duration of bioelectrical muscle activity) carried out Lehman (2005), Requena et al. (2005) and Welsch et al. (2005). In our research four main muscles involved in flat bench press indicates that the activity in the descent phase is much less than in the ascent phase. This is confirmed by the results obtained by Elliot et al. (1989), McCaw and Friday (1994), Anderson and Behm (2004) and Santana et al. (2007). Increasing load from 70% RM to 100% RM prompted measurable activity growth of studied muscles, both in ascent and descent phase. The exception is the *pectoralis major* and *triceps brachii* muscles which in the ascent phase with loading 100% RM showed decrease activity. Probably this decrease in the activity of these two muscles is associated (compensated) with increased activity of the *anterior deltoid* muscle.

The symptom of muscles getting involved in bench pressing is bar kinematics. what is characterized by the graph of acceleration. Acceleration graph clearly changes with increasing of the load. At the 70% and 80% RM loads registered only one region of acceleration and braking one, so at the greater load (90% and 100% RM) there are already four specific areas: acceleration phase. sticking region. maximum strength region and decleration phase (Lander et al., 1985). This four specific regions shows a lower smooth movement.

Acceleration characteristic is reflected in the velocity curve. In the bench pressing ascent phase at the 70% and 80% RM loads reaches one maximum velocity, and in attempts at 90% and 100% RM there are two. This decrease in the bar velocity is called *sticking point* (Van den Tillaar and Ettema, 2009).

The vertical bar displacement in the descent phase is smaller than in the ascent phase. As confirmed by the results Duffey and Challis (2007). This is probably the result of greater use of range of motion in ascent phase in the elbow and shoulder joints at the end of the movement. Differences in the change of the angle elbow joint and angle shoulder joint (only extension-flexion movement) are larger during the ascent phase. Noteworthy is also greater asymmetry between the right and left upper limb in both elbows and shoulders joints with increasing load (Figure 1F, 2F, 3F, and 4F).Very often ignored is the bar movement in the horizontal plane (from the shoulder towards the nipples contrariwise) during flat bench pressing (Siegel et al., 2002; Drinkwater et al., 2007; Pearson et al., 2009; Jandacka and Vaverka, 2009). This is unfounded as our research shows that the horizontal bar displacement (S_x – parallel to the line of the shoulders; S_z – from the shoulder towards the nipples contrariwise) are larger in the descent phase than in the ascent phase. This is confirmed by the results obtained by Elliot et al. (1989).

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VARIABILITY OF SELECTED KINEMATIC INDICATORS IN THE SHOT PUT TECHNIQUE DEPENDING ON THE STARTING CONDITIONS

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Abstract: The purpose of this study was to analyze the variability of selected kinematic (mainly release) indicators (of the athletes and the put) during the shot put competitions on the stadium (8 athletes-A group) and in the hall (6 athletes − B group). Each of them performed 6 trials, all videos were collected using 2 high speed digital cameras, placed on the performance field, perpendicular to each other. Only measured trials (34 in A group and 27 in B group) were analyzed using 3-D software APAS. The aim was to compare selected indicators using coefficient of variability (CV) and average relative error (AV) due to the technique (spin and glide) and the group (A and B). According to the AV and the CV release indicators of the athlete and the put have generally shown low variability (below 10% in at least the half of the cases). In 10 of 100 analyzed cases the variability was high (>20%), in 14 of 100 cases the variability was medium (10%-20%), in the rest cases the variability was small (<10%). Non-parametric statistical analysis was used to find indicators which have the significant influence on the distance of the throw (according to the group and technique used). There were mainly significant inverse correlations (at $p < 0.05$) between the distance and the AV of the selected indicators, which meant that the distance was longer when the value of variability (AV) was small.

Keywords: shot put, variability, release indicators, 3D kinematic analysis

INTRODUCTION

Throwing events in track and field (shot put, hammer throw, javelin throw and discus throw) have been the subject of a number of studies [3,5,6,7,13,14,17,19]. Good performance in mentioned track and field competitions has been mainly determined by the athlete's technique than the tactics.

The most popular method in analyzing technique, especially during competitions (but also during training sessions) has been video motion analysis (qualitative and quantitative). Xie Wei [26] in his research showed three using of

video analysis: technique analysis, monitoring the technique and technique improvement. For the technique analysis during starting conditions (competition) at least two digital cameras are used (to get three-dimensional parameters). It has been more frequently used method [4,9,11,20,27] than two-dimensional motion analysis which uses only one digital camera (move of the athlete only in sagittal plane). Mainly complex movements like shot put or discus throw require multidimensional analysis.

Spin and glide have been the main techniques used by athletes during shot put performances. Especially the spin shot put technique has been an extremely complex movement, which require a high level of motor control, bio-motor abilities and an optimal constitution of the thrower [8]. The initial movement in the shot put techniques has been generated by the muscles of the lower body segment (legs) than the final movement has been generated by the muscles of the upper body segment (arm-hand) [9].

Generally analyzed parameters in the studies about throwing events such as shot put have been release parameters: height of release, angle of release and release velocity. Among these parameters release velocity has been the most important as the horizontal displacement of the shot has been proportional to velocity squared [18]. The correlation between release velocity and the measured distance has been very strong. Release velocity has been generated by preceding phases, especially the second double support phase [9]. To throw the put over 21 m, release velocity in excess of 13,5 m/s is necessary [27]. According to the study of Judge et.al. [16] a summation of forces from the various phases of the throw and the various body segments has been needed to achieve maximum velocity at the moment of release. Release speed has been also inversely proportional to the angle of release [15,24]. Release speed decreases with the increase of the angle, approximately 1.7 (m/s)/rad and decreases with the increase in height, approximately 0.8 (m/s)/m.

Angle of release has been the second most important factor in the projectile motion equation. It has been determined by the angle of the throwing arm and the orientation of the trunk relative to the ground. In Young's study [27], the release angles ranged from 32° to 39° with a mean of 35° that have been similar to the values reported in studies on both elite and non elite shot putters [1,7,20,22,23].

For the best shot-putters, the height of release has been between 2 and 2,2,m [1,2,23]. According to McCoy et.al. [20], Pyka and Ortando [21] and Hay [12] the height of release has been mainly determined by the athlete's anthropometric parameters (the height and the lenght/span of the throwing arm).

According to the studies of Michael Young [27] among elite female shot putters, greater rear knee flexion at rear foot touch-down and release, increased release speed, a more neutral shoulder-hip angle at release and a greater horizontal release distance were the best predictors of measured distance. Measured distance was inversely associated with rear knee angle at rear toot touch-down and rear knee

angle at release, both push off leg angle at take off, release angle were also observed to be highly correlated with rear knee angle at rear foot touch-down and shoulder hip separation at release was found to be correlated with distance.

Young et. al. [27]) and Tsirakos et. al. [23] found no crucial relationship between the measured distance and either the temporal parameters or the implement speeds or accelerations before release.

Alexander et. al. [1] examined 31 males and 30 females shot putters to determine which parameters were most critical for success in the event. They noticed that, for the female throwers, the most critical parameters to produce longer trials are: knee extension during the glide, elbow speed during delivery, and a greater shoulder flexion angle at release while for the male throwers: center of mass speed during glide, vertical acceleration of center of mass during delivery, and trunk angle at the start of glide. The aim of this study was to compare the variability of selected kinematic indicators of the athlete and the put performed in two different starting condition: on the stadium and in the athletics hall using average coefficient of variability (CV). Additionally the aim of the study was to assess the relationship between average relative errors of selected biomechanical indicators (of the athlete and the put) and the distance of the throw.

MATERIAL

Fourteen word-class (right-handed) competitors took place in this analysis. Eight of them (5 using spin technique and 3 using glide technique) performed trials during international competition on the track and field stadium (group A) and six of them (3 using spin technique and three using glide technique) performed trials during national championship in the athletics hall (group B). According to the table 1 shot-putters from group A using glide technique were slightly taller (on average 3 cm), had greater weight and BMI (on average 7,2 kg and 0,6 kg/m^2) and were a little older (on average 1,3 years) than shot-putters using spin technique in the same group.

TABLE 1. Anthropometric data (x ± SD) of 8 shot putters (group A)

GROUP A	Age [lata] x±SD	Body height [m] x±SD	Body mass [m] x±SD	BMI [kg/m^2] x±SD
SPIN	25±1	1,92±0,07	116,8±8,6	31,9±1,1
GLIDE	26,3±3,2	1,95±0,08	124±6,9	32,5±0,8

Similar dependance but slightly greater differences between two techniques were among athletes in group B (table 2). Athletes using glide technique were on average 3,7 years older, 3cm taller, 12,7 kg heavier and have about 2,4 kg/m^2 greater BMI than athletes using spin technique. There were no significant

differences (at p<0,05) for the height of the athlete's center of gravity according to the group and the technique used $(F_{(1,7)}=0,7484, p=0,416)$.

TABLE 2. Anthropometric data (x±SD) of 6 shot putters (group B)

GROUP B	Age [years] x±SD	Body height [m] x±SD	Body mass [m] x±SD	BMI [kg/m^2] x±SD
SPIN	22±2	1,89±0,02	110±7,1	30,9±1,3
GLIDE	25,7±2,5	1,92±0,06	122,7±6,1	33,3±1,6

Each athlete performed 6 attempts during competition in the final session. Only measured trials (34 in group A and 27 in group B) were analyzed.

In table 3 athletes from group A and in table 4 athletes from group B were classified according to the place during competition (1-8 in group A and 1-6 in group B) including average and maximal distances of the measured trials.

TABLE 3. Mean and maximal distances of the measured trials among athletes using spin technique–S (athletes: 2,4,5,6,7) and glide technique-G (athletes: 1,3,8) during competition on the stadium (group A)

Athlete (according to the place: 1-8)	Mean distance / max. result [m] (the number of measured trials)
1 A (G)	20,41 / 20,62 (2)
2 A (S)	19,94 / 20,22 (5)
3 A (G)	19,91 / 20,20 (5)
4 A (S)	19,27 / 19,42 (3)
5 A (S)	18,90 / 19,18 (6)
6 A (S)	18,44 / 19,00 (2)
7 A (S)	18,07 / 18,31 (5)
8 A (G)	18,15 / 18,26 (6)

TABLE 4. Mean and maximal distances of the trials among competitors using spin (S) technique (athlete: 1,5,6) and glide (G) technique (athlete: 2,3,4) during competition in the hall (group B)

Athlete (according to the place: 1-6)	Mean distance / max. result [m] (the number of measured trials)
1 B (S)	18,77 / 18,94 (5)
2 B (G)	18,16 / 18,80 (4)
3 B (G)	18,04 / 18,52 (4)
4 B (G)	17,77 / 18,41 (6)
5 B (S)	17,62 / 18,16 (5)
6 B (S)	17,71 / 18,15 (3)

In group A (table 3), 5 athletes using spin technique performed 21 measured trials while 3 athletes using glide technique performed 13 measured trials. In group

B (table 4), 3 athletes using spin technique performed 13 measured trials while 3 using glide technique – 14. Average and maximal distances in both techniques in group A were higher than in group B.

METHODS

Two high speed digital cameras (JVC, model GR DVL-9800,) set on the tripods, were placed perpendicular to each other (two cameras fixed at an angle of 90˚ between their optical axes) near the shot put throwing circle. All throws, performed by 8 competitors in group A and 6 competitors in group B at the preliminary and finals during international and national competitions, were recorded at 60 frames per second and then analyzed using Ariel Performance Analysis System (APAS). Synchronized data sequences from each of the cameras views were utilized. For each camera view, 18 points were digitized, 16 points were placed on the athlete body including big toe, ankle, knee, hip, wrist, elbow and shoulder for the left and right side of the body as well as the right hand, the chin and the top of the head. The seventeenth landmark/point was place on the center of the put and the last eighteenth was placed on the right side edge of toe-board of the throwing circle. The analyzed area of the throwing circle was calibrated with a 1,5m x 2m x 1,5m reference scaling frame. The calibration frame was based on eight reference edges (Figure 1) and was performed before and after competition session.

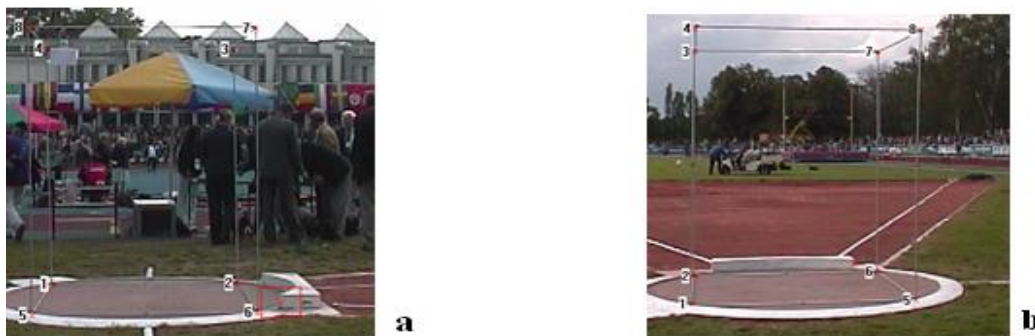**FIGURE 1.** Camera views of the calibration frame (a – view from the right side of the throwing circle and b – view from the back of the throwing circle).

Following kinematic indicators of the athlete (CG – athlete's center of gravity in case of velocities) and the put (P – the center of the put) during release (RLS - the last contact of the athlete's) were taken into account during analysis including only measured trials:

- Release angle (γ) - the relative angle between the trajectory of the put and the horizontal axis/plane. Release angle is a vector variable resulting from a combination of the horizontal and vertical forces in the release action.
- Height of release (H) - the height of the center of the put above the surface of the circle at release.
- Height of the center of the body during release (h) - the height of the center of body mass above the surface of the circle at the moment of release.
- Distance of the throw (D) – the horizontal displacement of the put from the innermost edge of the toe-board to landing. This is the distance recorded as the official result.
- Resultant velocity (Vw) of the athlete's center of gravity (CG) and the center of the put (P).
- Horizontal velocity (Vx) of the athlete's center of gravity (CG) and the center of the put (P).
- Vertical velocity (Vy) of the athlete's center of gravity (CG) and the center of the put (P)
- Shoulder-hip separation (S-H) during RLS. S-H is the orientation of the hips relative to the shoulders. A neutral position (0˚separation) occurs when the shoulders and hips are aligned with one another. A positive angle occurs when the throwing side shoulder is posterior to the throwing side hip.
- Rear (right) and front (left) knee angle ($β\_p$ and $β\_l$, respectively) - relative angle between thigh and leg segments.
- Shoulder and elbow angle of the right (throwing) arm ($φ\_p$ and $δ\_l$, respectively).
- Right and left hip angle ($λ\_p$ and $λ\_l$, respectively).

Additionaly path components of the athlete's center of gravity and the center of the shot were calculated:
- x_CG, y_CG, z_CG, R_CG [m] – respectively the distance in horizontal, vertical, lateral directions and resultant of the athlete's center of gravity movement;
- x_P, y_P, z_P, R_P [m] - respectively the distance in horizontal, vertical, lateral directions and resultant of the put movement.

Mean and standard deviations were determined for the examined indicators of the athletes and the put in all measured trials (in spin and glide technique in group A-stadium and group B-hall). Differences between variables were compared using the average coefficient of variability (CV) and the average relative error (AV): CV = SD / Xav [%] and AV = X – Xav / Xav [%], where: CV – coefficient of variability, AV – average relevant error, SD – standard deviation, X – value of each release indicator, for each athlete, Xav-average value of each release indicator according the group and technique used. The lower the CV, the lower the

variability was. It was assumed that CV<10%-low variability, 10%-20%-medium variability, >20%-high variability.

Two-factor analysis of variance (ANOVA) was used to analyze significant differences in athletes' body height and another release and path indicators depending on the two factors: the GROUP and/or the TECHNIQUE. Relationships between selected indicators were determined using non-parametric Spearman correlation coefficient. All statistical analysis were based on the average relative error (AV) of selected indicators. The use of the AV allowed to take into statistical analysis all shot-put measured trials (what was not possible when it came to the CV, mainly due to the small size of the study group). The values of the distance of the throws were used in the Spearman correlation analysis with the AV of the selected indicators to find the most important relationships between them. Probability level at p<0,05 was taken to asses the significance of existing differences and relationships. Statistical package: StatSoft, Inc. STATISTICA v. 7 was used to all analysis.

RESULTS

According to the mean values (table 5), the angle indicators like: right knee angle (β_p), left hip angle (λ_l) lateral and resultant path of the athlete's center of gravity and the center of the put (respectively z_CG, R_CG, z_P, R_P), differed more for the spin technique than for the glide one. The most similar values (without the division into the groups and techniques) were for the height (h) and the distance in horizontal direction of the athlete's center of gravity movement (x_CG). Right hip angle (λ_p), horizontal velocity of the athlete's center of gravity (Vy CG), the height of the put (H) and the angle of release (γ) differed more for the glide technique.

TABLE 5. Average values (±SD) for the release and the distance in horizontal, vertical lateral direction and resultant distance of the athletes center of gravity (CG) and the center of the put (P) movement according to the group (A-stadium and B-hall) and the technique used (S-spin and G-glide)

	A		B	
	S	G	S	G
β_p [°]	148,31±10,16	141,74±11,06	150,00±16,14	133,04±34,56
β_l [°]	168,31±6,18	172,83±3,31	170,25±4,71	175,92±3,03
φ_p [°]	122,54±4,43	131,80±3,83	121,03±7,49	121,83±14,01
δ_p [°]	162,01±9,63	164,09±7,82	147,55±15,78	137,06±14,61
λ_p [°]	167,89±5,90	171,46±3,71	162,76±7,18	169,05±5,54

λ_1 [°]	156,11±7,30	141,95±5,23	147,77±4,26	139,98±8,97
S-H [°]	23,99±11,00	30,56±6,28	31,95±12,48	22,75±6,59
VxSC [m/s]	0,55±0,20	0,72±0,32	0,60±0,13	0,79±0,22
VySC [m/s]	0,99±0,28	0,92±0,17	1,31±0,46	1,15±0,28
VwSC [m/s]	1,22±0,26	1,2±0,25	1,52±0,39	1,42±0,31
h [m]	1,23±0,07	1,23±0,06	1,22±0,08	1,24±0,03
VxP [m/s]	10,23±0,50	9,77±0,68	9,49±0,83	9,13±0,90
VyP [m/s]	7,57±0,33	7,86±0,33	6,97±0,60	7,55±1,10
VwP [m/s]	12,76±0,41	12,66±0,46	11,83±0,79	11,93±0,87
H [m]	2,18± 0,11	2,27± 0,06	2,16±0,16	2,27±0,16
γ [°]	37,75±3,32	39,40± 2,88	36,35±2,86	39,57±5,41
D [m]	18,95±0,74	19,18±1,02	18,08±0,6	17,91±0,5
x_CG [m]	1,56±0,09	1,57±0,11	1,57±0,05	1,58±0,41
y_CG [m]	0,71±0,08	0,76±0,15	0,72±0,09	0,74±0,20
z_CG [m]	0,72±0,13	0,21±0,04	0,79±0,07	0,23±0,08
R_CG [m]	2,04±0,12	1,87±0,18	2,15±0,05	1,87±0,49
x_P [m]	3,91±0,39	3,71±0,37	3,42±0,41	3,20±0,87
y_P [m]	2,37±0,31	2,6±0,25	2,07±0,16	2,10±0,64
z_P [m]	1,78±0,22	0,71±0,23	1,68±0,24	0,47±0,15
R_P [m]	5,42±0,47	4,74±0,49	4,88±0,47	4,04±1,09

TABLE 6. Average percentage values of the coefficient of variability (CV) for the distance and the angle indicators of the athlete's and the shot (P) in group A (stadium) and in group B (hall) with the division into spin (S) and glide (G) technique

	CG	P									
	h	H	D	γ	φ_p	σ_p	λ_p	λ_1	β_p	β_1	S-H
S	1	1,6	1,8	4,4	3,4	4,8	2,8	1,8	2,4	1,4	26,6
G	1,3	1,7	1	6	1,7	3,7	2,3	1,3	2,7	1,3	12,7
S	2,3	4,7	1	6,7	3	8	3,3	3	4,3	2,3	39,7
G	2,7	7	2,7	6,7	11,7	11,3	3,3	3	3,3	1,3	26

The greatest differences between groups according to the technique was found for the S-H (table 7). The lowest differences (below 1%) in spin technique existed for the angle of the right shoulder and elbow, the angle of the left knee and for the measured distance. In glide techniques the lowest differences were observed for the left knee angle, the angle of release and the angle of the right hip. The most similar differences (below 1%) between spin and glide technique were found for the height of the athlete's center of gravity (h), distance of the throw (D), right and left hip angle and left knee angle (table 7).

TABLE 7. Average percentage differences between the groups for the coefficient of variability (CV) due to the technique for the distance and angle indicators of the athlete and the put

	CG	P									
	h	H	D	γ	φ_p	σ_p	λ_p	λ_l	β_p	β_l	S-H
S	1,3	3,1	0,8	2,3	0,4	3,2	0,5	1,2	1,9	0,9	13,1
G	1,4	5,3	1,7	0,7	10	7,6	1	1,7	0,6	0	13,3

TABLE 8. Average percentage values of the coefficient of variability (CV) for velocity indicators and the distances in horizontal, vertical, lateral directions and resultant distance of the athlete's center of gravity (CG) and the center of the put (P) movement in group A (stadium) and in group B (hall) with the division into spin (S) and glide (G) technique

		CG							P						
		x	y	z	R	Vx	Vy	Vw	x	y	z	R	Vx	Vy	Vw
A	S	2,4	3,2	6,2	2,5	34,4	12,6	8,4	7,3	8,3	9,1	6,3	3	3	2,6
	G	6,2	14,8	18,6	9,1	27,3	14	12	9,0	7,2	18,5	8,1	2	4,7	1,7
B	S	2,4	5,2	1,8	2,4	23,3	25,7	17,3	6,3	7,5	4,8	5,4	8,3	8	7
	G	2,5	5,1	17,0	2,5	22,7	25	20,3	9,7	15,6	13,1	8,8	7,3	14	6,7

Among velocity indicators and the distances (in horizontal, vertical, lateral and resultant directions) of the athlete's center of gravity (CG) and the center of the put (P) movement (table 8), the greatest variability (CV>20%) was found for the horizontal velocity of the athlete's center of gravity in both group and techniques. The high variability was observed also for the vertical velocity of the athlete's center of gravity in spin and glide techniques in group B. The lowest variability (below 10% in both groups and techniques existed for the distances in horizontal and resultant directions of the athlete's center of gravity and the put movement (respectively x_CG, R-CG, x_P, R_P). The velocity indicators of the put showed

lower variability (below 10%) in both groups and techniques than velocity indicators of the athlete's center of gravity (high and medium variability). The greatest difference (15,2%) between spin and glide technique was found for the distance in lateral direction of the CG movement in group B. In group A the greatest difference of 13,1% existed for the horizontal velocity of the CG. On the other hand the lowest differences (0,9%-1%) between techniques in group A were found for the horizontal and resultant velocity of the put. In group B the lowest differences (0,1%-1%) existed for the distances in horizontal, vertical and resultant directions of the CG movement, vertical velocity of the CG and the horizontal velocity of the CG and the P.

The greatest CV differences (>10%) between the groups according to the technique were found for the vertical velocity of the CG in both techniques and the horizontal velocity of the CG in spin technique (table 9). The lowest values of differences in spin technique existed mainly for all distance components of the CG and P, respectively in glide technique for the distance in horizontal direction of CG and P movement, distance in lateral direction of the CG movement and resultant distance of the P movement.

TABLE 9. Average percentage differences between the groups for the coefficient of variability (CV) due to the technique for the velocity indicators and the path components of the athlete's center of gravity (CG) and the center of the put (P)

	CG							P						
	x	y	z	R	Vx	Vy	Vw	x	y	z	R	Vx	Vy	Vw
S	0	3	4,4	0,1	11,1	13,1	8,9	1	0,8	4,3	0,9	5,3	5	4,4
G	3,7	9,7	1,6	6,6	4,6	11	8,3	0,7	8,4	5,4	0,7	5,3	9,3	5

Following tables have been connected with the same indicators as mentioned before but according to the AV (instead of the CV).

The greatest differences were found for the S-H in both groups and techniques. The rest of the indicators of the athlete's and the put (due to the AV) had the small value (below 10% - table 10).

Also the greatest differences according the spin and glide technique between group A and B has been seen for the S-H (table 11). For the rest indicators in spin technique the differences between groups were: 0,3%-3,5%, in glide technique between 0,1% and 7,5%. The greatest difference between spin and glide technique existed for the angle of release (3,8%) and the lowest one for the height of the put and the right hip angle (0,3%).

TABLE 10. Average percentage values of the average relative error (AV) for the distance and the angle indicators of the athlete's and the put (P) in group A (stadium) and in group B (hall) with the division into spin (S) and glide (G) technique

		CG	P									
		h	H	D	γ	φ_p	σ_p	λ_p	λ_l	β_p	β_l	S-H
A	S	5,0	1,2	1,9	3,2	2,8	3,6	2,1	1,4	1,8	1,2	20,5
	G	1,0	1,4	0,8	4,4	1,2	2,7	1,5	0,9	1,9	1,2	9,3
B	S	1,5	3,8	1,3	4,9	2,5	6,4	2,8	2,3	3,4	1,8	32,8
	G	1,9	4,3	2,3	9,9	8,7	9,8	2,5	2,4	2,3	1,1	19,4

TABLE 11. Average percentage differences between the groups for the average relative error (AV) due to the technique for the distance and the angle indicators of the athlete and the put

	CG	P									
	h	H	D	γ	φ_p	σ_p	λ_p	λ_l	β_p	β_l	S-H
S	3,5	2,6	0,6	1,7	0,3	2,8	0,7	0,9	1,6	0,6	12,3
G	0,9	2,9	1,5	5,5	7,5	7,1	1,0	1,5	0,4	0,1	10,1

TABLE 12. Average percentage values of the average relative error (AV) for the velocity indicators and the distances in horizontal, vertical, lateral directions and the resultant distance of the athlete's center of gravity (CG) and the center of the put (P) movement in group A (stadium) and in group B (hall) with the division into spin (S) and glide (G) technique

		CG							P						
		x	y	z	R	Vx	Vy	Vw	x	y	z	R	Vx	Vy	Vw
A	S	1,9	2,3	4,6	1,8	21,8	9,0	6,2	5,7	6,2	6,7	4,9	2,2	2,3	1,4
	G	4,2	10,2	13,7	6,2	20,6	17,7	8,7	6,2	4,9	13,8	5,5	1,6	3,6	1,3
B	S	1,8	3,4	6,0	1,8	17,6	20,0	13,1	5,0	5,7	3,5	4,2	5,9	5,9	5,1
	G	2,1	3,9	13,2	2,0	18,4	18,7	15,6	7,2	11,7	9,6	6,8	5,1	10,4	5,1

The greatest values of the AV (about 20%) were found for the horizontal velocity of the CG in both groups and techniques and for the vertical velocity of the CG except the spin technique in group A (table 12). The AV of the put velocities were definitely lower than the velocities of the athlete's center of gravity. Generally lower values of the AV for the athlete's center of gravity than the put were for the horizontal and resultant path of the CG.

As is shown in table 13, all differences between groups according to the spin and glide technique were below 7%. The greatest differences (in these cases above 5%) were found for the resultant velocity of the athlete's center of gravity in both techniques and for the vertical path and vertical velocity of the put in glide technique.

TABLE 13. Average percentage differences between the groups for the average relative error (AV) due to the technique for the velocity indicators and the path components of the athlete's center of gravity (CG) and the center of the put (P)

	CG							P						
	x	y	z	xyz	Vx	Vy	Vw	x	y	z	xyz	Vx	Vy	Vw
S	0,1	1,1	2,6	0	4,2	11	6,9	0,7	0,5	3,2	0,7	3,7	3,6	3,7
G	2,1	6,3	0,5	4,2	2,2	1	6,9	1	6,8	4,2	1,3	3,5	6,8	3,8

The lowest differences between groups (<1%) were found for the horizontal and resultant path of the CG and P in spin technique and resultant path in glide technique. The most comparable differences (<1%) between spin and glide technique existed for the resultant velocity of the CG and the P, for the horizontal, lateral and resultant path of the put (table 13).

Significant inverse correlations were obtained for the AV (at $p<0,05$) between the distance of the throw and the AV of: the angle of the right elbow ($r=-0,294$), height of the athlete's center of gravity ($r=-0,332$), angle of release ($r=-0,275$), horizontal and resultant velocity of the shot (respectively $r=-0,415$, $r=-0,558$). Insignificant proportional relationship existed between the distance and the AV of the right hip angle. Insignificant inverse relationships were obtained between the distance and the AV of the rest indicators of the put and athlete.

Significant inverse relationships (at $p<0,05$) between the distance and the AV of: the angle of the right knee ($r=-0,381$), shoulder-hip separation ($r=-0,427$), horizontal and the resultant velocity of the put (respectively $r=-0,411$, $r=-0,693$) and angle of release ($r=-0,345$) were observed for spin technique. Insignificant inverse relationships were between the distance and the angle of left knee, angle of the right elbow, angle of the left hip, horizontal and resultant velocity of the athlete's center of gravity, height of the athlete's center of gravity, vertical velocity

of the put and height of the put. Insignificant proportional relationships existed between the distance and the AV for the rest four angles and velocity release indicators.

Significant inverse correlation (at p<0,05) between the distance and the AV of the horizontal velocity of the put (r=-0,470) was observed for the glide technique. Insignificant inverse relationships existed between the distance and the AV of the rest of the release indicators of the athlete's and the put.

Significant inverse correlation (at p<0,05) between the distance and the AV of the resultant velocity of the shot (r=-0,628) was observed for the spin technique and group A (stadium). Insignificant proportional relationships were mainly between the distance and the AV of: the angle of the left hip and vertical velocity of the athlete's center of gravity. Insignificant inverse relationships were found mainly between the distance and the AV of the horizontal velocity of the put and the angle of release.

Significant inverse correlation (at p<0,05) between the distance and AV of the angle of the right knee (r=0,610) was observed for the spin technique and group B (hall). Insignificant proportional relationships were mainly between the distance and the AV of: the angle of the right shoulder, resultant velocity of the athlete's center of gravity and height of the shot. Insignificant inverse relationships existed between the distance and the rest seven angle and velocity release indicators of the CG and the P.

Significant inverse correlations (at p<0,05) between the distance and the AV of: the height of the athlete's center of gravity (r=-0,615), horizontal and vertical velocity of the athlete's center of gravity (respectively r=-0.593, r=-0,718) were observed for the glide technique and group A (stadium). Insignificant proportional relationships were found mainly between the distance and the AV of: the angle of the right knee, angle of the right and left hip, resultant velocity of the put and angle of release. Insignificant inverse relationships existed mainly between the distance and the AV of: the angle of the left knee, resultant velocity of the athlete's center of gravity and horizontal velocity of the put.

Significant inverse correlations (at p<0,05) between the distance and the AV of the angle of the right and left knee (respectively r=-0,636, r=-0,541) were observed for the glide technique and group B. Insignificant proportional relationships were found mainly between the distance and the AV of the vertical velocity of the put and height of release. Insignificant inverse relationships existed mainly between the distance and the AV of the right hip angle and horizontal velocity of the shot.

Significant differences according to the group were obtained for the AV of: the angle of the right elbow (F(1,57)=35,432, p≤0,0001), angle of the right hip (F(1,57)=14,890, p≤0,001) angle of the right shoulder (F(1,57)=16,306, p=0002), shoulder-hip separation (F(1,57)=9,545, p=0,003), horizontal velocity of the athlete's center of gravity (F(1,57)=7,547, p=0,008), the horizontal, vertical and

resultant velocity of the put (respectively $F(1,57)=10,657$, $p=0,002$, $F(1,57)=16,897$, $p\leq0,001$, $F(1,57)=28,846$, $p\leq0,001$), height of the put ($F(1,57)=13,0$, $p\leq0,001$), angle of release ($F(1,57)=9,552$, $p=0,003$). Significant differences according to the technique were obtained for the AV of: the angle of the right shoulder ($F(1,57)=5,461$, $p=0,002$), shoulder-hip separation ($F(1,57)=10,462$, $p=0,002$), horizontal velocity of the put ($F(1,57)=6,052$, $p=0,017$) and for the angle of release ($F(1,57)=6,950$, $p=0,011$). Significant differences according both to the group and the technique existed for the AV of: the angle of the right shoulder ($F(1,57)=18,377$, $p\leq0,001$), angle of the right elbow ($F(1,57)=4,574$, $p=0,037$), vertical velocity of the put ($F(1,57)=4, 766$, $p=0,332$), angle of release ($F(1,57)=4,887$, $p=0,031$) and distance of the throw ($F(1,57)=14,417$, $p\leq0,001$).

There were found insignificant correlations (at $p<0,05$) between the distance of the throw and the AV of the distance components of the athlete's center of gravity and the center of the put movement (without the division into the group and the technique). The distance was found to be proportional to the AV of the distance in horizontal, vertical and resultant direction of the CG movement and distance in horizontal direction of the P movement.

Significant correlation between the distance of the throw and the AV of the distance in vertical direction of the CG movement($r=-0,573$) was observed for the spin technique: the higher the AV of the x_CG, the lower value of the distance was. Insignificant proportional correlations with the distance of the throw were found for the AV of: the R_CG, x_P, y_P and R_p. The inverse, insignificant correlations with the distance were found mainly for the AV of distance components of the CG movement.

Significant correlation (at $p<0,05$) between the distance of the throw and the AV of the R_P ($r=0,416$) was observed for the glide technique: the higher the value of AV for the R_P, the higher the value of the distance was. Insignificant proportional correlation with the distance existed for the AV of: the x_CG, y_CG and z_P. The inverse, insignificant correlations with the distance were found mainly for the AV of the distance components of the P movement.

Significant proportional correlations (at $p<0,05$) between the distance of the throw and the AV of the x_P and R_P (respectively $r=0,552$, $r=0,437$) were observed for the spin technique and group A. Inverse significant correlations were found between the distance and the AV of the y_CG ($r=-0,537$) and z_P ($-0,457$). Insignificant proportional correlations existed between the distance and the AV of the x_CG, R_CG and y_.P.

There were no significant correlations (at $p<0,05$) found between the distance and the AV of the distance components of the CG and the P movement observed for spin technique and group B. Insignificant proportional correlations existed between the distance and the AV of: z_CG, R_CG and y_P. The inverse

insignificant correlation was found for the AV of: the x_CG, y_CG, x_P, z_P and R_P.

- No significant correlations (at p<0,05) were found between the distance of the throw and the AV of the distance components of the CG and the P movement observed for the glide technique and group A. Insignificant proportional correlations existed between the distance and the AV of the distance components of the CG. movement. Insignificant inverse correlations were observed between the distance and the AV of the distance components of the put movement.

- Significant correlation (at p<0,05) between the distance of the throw and the AV of the z_CG (r=-0,572) was found for the glide technique and group B.

- Significant differences (according to the group) were observed for the AV of the: R_P (F(1,57)=8,107, p=0,006), and z_P (F(1,57)=6,042, p=0,017). Significant differences (according to the technique) were found for the AV of the x_CG, y_CG, z_CG and R_P (respectively F(1,57)=5,795, p=0,019, F(1,57)=11,670, p=0,001, F(1,57)=17,312, p≤0,001, F(1,57)=9,464, p=0,003) and for the AV of the z_P (F(1,57)=16,414, p≤0,001). Significant differences (for the group and the technique) existed for the AV of x_CG, y_CG and R_P (respectively F(1,57)=4,982, p=0,030, F(1,57)=10,640, p=0,002, F(1,57)=8,205, p=0,006).

DISCUSSION

The use of 3D video motion analysis has been helpful for athletes and their coaches to analyze the technique they use (spin or glide) and to find ways to increase the efficiency and improve performance.

Release indicators have been frequently examined in the competition like shot put [15,18]. According to the literature, the most important influence on the distance were found for the resultant velocity of the shot, the angle of release and the height of the center of the put during release (the last frame when the put has had the contact with the throwing hand). The last indicator has been dependent on human anthropometric, especially the height and the length of the throwing arm [1,12,20] so might be only little trained in the training process. Indicators like the height of the athlete's center of gravity and the height of the center of the put have been low variable ones (variability below 5%), according to the CV and AV regardless of the group and the technique. The comparison of selected release indicators for two different groups of athletes during indoor competition (our study group B and comparative group D from the study of Gutiérrez-Davila [10]) has also confirmed that the height of the put at the moment of release had relatively constant and low variability (below 10% according to the CV)

Another researches have shown that the angle of release among some athletes using spin techniques varies more than among athletes using glide technique. It has probably been caused by the greater deviations during spin phase connected with the lower stability of the athlete. The height of release and some external factors has influenced the angle of release in lower degree than for example during discus or javelin throw.

Also greater variability (according to the CV and AV) of selected indicators in group B has been caused by the lower level of this competition and the participation of a little worse athletes (in group B the best throws were below 19m while in group D all throws were over 20m).

Generally, release indicators were observed to be very comparable (low CV and AV) indicators in the shot put. Slightly lower variability was found during competition on the stadium (the greatest difference in variability between group A and B without division into two techniques existed for the vertical velocity of the athlete's center of gravity and the lowest one for the angle of the left knee). In spin technique the greatest differences between group A and B were found for the shoulder-hip separation, vertical and horizontal velocity of the athlete's center of gravity and the lowest for the right shoulder, right hip angle and left knee angle. In glide technique the greatest differences were observed also for the shoulder-hip separation, vertical velocity of the CG and vertical velocity of the put. The lowest differences were found for the angle of release and right and left knee angle. Only for the horizontal velocity of the athlete's center of gravity general average variability (all in spin and glide technique) in group A was found to be greater than in group B. In other cases, less variabilities (according to the CV and AV) were observed for the indicators of the put and the athlete in group performed on the stadium.

The coefficient of variability and the average relative error for the 8 finalists from our study group A-stadium (5 using spin and 3 using glide technique) compared to the group C (according to the study of Wilko Shaa [25]) with also 8 athletes (5 using spin and 3 using glide technique) have shown similar low variability (according to the CV and AV) for the angle of release (in all cases below 5%) and the distance of the throw (below 2%).

There were found few significant correlations (at $p < 0,05$) in the study between the distance of the throw and the AV of the selected release indicators. In spin technique there were observed 4 and in glide technique – 1 (in both groups) significant inverse relationships, which meant that the lower value of the variability (AV) the longer the distance of the throw was. There were found 13 of 16 and 15 of 16 (respectively for the spin and glide technique) inverse relationships between the distance and selected release indicators. There were 11 of 16 inverse relationships observed both for group A (stadium) and group B (hall).

In case of the AV of the distance of CG and P movement there were found 6 significant correlation (at p<0,05) with the distance of the throw: 1 inverse correlation (out of 8 correlations) for spin technique, the same for glide technique and group B, also one for the group A, 1 proportional correlation for glide technique, 4 significant correlations (two of them inverse and two proportional correlations) for spin technique and group A. Inverse correlation meant that the lower value of the AV (lower variability) of selected indicators, the longer the distance of the throw was.

There were found no significant correlations (at p<0,05) between the distance of the throw and the AV of the distances in horizontal, vertical, lateral directions and resultant distance of of CG and P movement observed for the all group (without GROUP and/or TECHNIQUE factors).

CONCLUSIONS

- The variability of release indicators were found to be the low variable ones (below 10% according to the AV and CV), especially in group A (stadium) compared to group B (hall). On one hand it could be because of the genetic related factors (on which we have very small influence during training session, like the height of the put and the center of the athlete's center of gravity), on the other hand the higher sport level has caused more stable technique.
- All the statistical significant correlations between the distance of the throw and the AV of selected release indicators has had inverse correlations which meant that the lower variability of the indicator, the longer the distance was. 44 of 124 insignificant correlations were proportional (the higher the variability, the longer the distance was) or the AV regardless of the distance of the throw was the same. The inverse correlations between the distance and the AV of the angle of the right knee were for the TECHNIQUE (spin) factor, for the GROUP factor (group B) and the GROUP and TECHNIQUE (spin technique in group B) factors. According to the TECHNIQUE factor (spin and glide) there was similar inverse significant correlation for the horizontal velocity of the put. In 4 cases there were significant inverse correlations between the distance and the resultant velocity of the P: according to the TECHNIQUE factor (spin), the GROUP factor (group B), GROUP and TECHNIQUE (group A and spin technique) and without division into GROUP and/or GROUP factor. No significant correlations (at p<0,05) were found for the GROUP factor.
- Three of seven significant correlations between the distance and the AV of the distance components of the CG and the P have been proportional ones. The inverse significant correlation with the distance of the throw was for the distance in vertical direction of CG movement according to the TECHNUIQUE factor (spin) and TECHNIQUE with GROUP factors (spin technique and group

A). There were observed about half (37 of 64) proportional insignificant correlations (at p<0,05) which meant that the lower the AV of selected distance component of the CG and/or the CG, the longer the distance was.

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TAKEOFF MECHANICS OF THE ACROBATIC TUMBLING EXERCISES (CASE STUDY)

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Abstract: Complex methodology was applied to study a movement structure of acrobatic tumbling elements (tucked and piked backward somersault, handspring and counter movement jump). We checked the usefulness of the multimodular measuring system (SMART, BTS, Company, Italy) and force plate (Kistler 9182C). Smart Analyser Software was used to create a database allowing the chosen parameters to be compared. The aim of this study was to determine the effectiveness of takeoff (bounce), and changes in the mechanical motion parameters and bioelectrical activity of muscles in selected *acrobatic tumbling elements with the flight phase*. Using a comprehensive methodology in the studies of these tumbling elements allows the presentation of the external and internal structure of the movement of this exercise. The backward piked somersault compared to the backward tucked somersault, required, at a lower flight altitude, higher angular momentum developed at the end of the take-off phase.

Keywords: acrobatic tumbling elements, electromyography, force platform, infrared cameras, movement analysis

INTRODUCTION

Over the last half century, there has been a significant increase the difficulty of elements, sequences and combination exercises in gymnastics. Before 1972, the backward somersault (a Salto) on the balance beam was not performed. Now, somersaults with the rotation around the longitudinal axis of the body (a Twist) are performed. In modern artistic gymnastics, the standing acrobatic tumblings are performed only in balance beam combinations. Knoll (1996) and McLaughlin et al. (1995) showed significant differences between the takeoff (bounce) to the somersault during jump down from the balance beam and acrobatic sequences on the floor. Despite this, when preparing to exercise on the balance beam, acrobatic elements on the floor are performed as an essential part of the balance beam training (Żołnierowicz and Plichta, 2001).

McNeal et al. (2007) have shown, that due to muscle activity during the takeoff to the tumbling sequence, the performance of simple acrobatic tumbling exercises

are the best way to improve the effectiveness of this phase. Most of the more or less complicated acrobatic tumbling exercises are performed backward. There are advantageous anatomical conditions for the backward takeoff (Knoll, 1996). The performance of the somersaulting skill is dependent on the linear and angular momentum at bounce and the configuration changes used by the gymnast during flight. The two most important factors for a successful performance are the vertical velocity of the centre of mass (COM) and the angular momentum around the mass centre at takeoff (Bruggemann, 1987; Hwang et al., 1990). The result of these two factors dictates how much somersault rotation can be achieved. Handsprings and the more simple spikes (jumps) no longer pose such requirements.

There are three fundamental acrobatic exercises: the forward roll, the backward roll, and the handstand. These elements are the starting point for teaching acrobatics in artistic gymnastics (Żołnierowicz and Plichta, 2001). On this basis, simple and then more complicated acrobatic evolutions (elements) are built. Exercises elements performed on the balance beam and on the floor are divided into 5 groups according to refereeing provisions (2013-2016 Code of Points, Federation Internationale de Gymnastique, 2013). The hardest and most diverse is a group of *acrobatic elements with the flight phase*. Of this group, standing backward tucked somersault (TS), standing backward piked somersault (PS), and standing backward handspring in place were selected for analysis (HS; Figure 1).
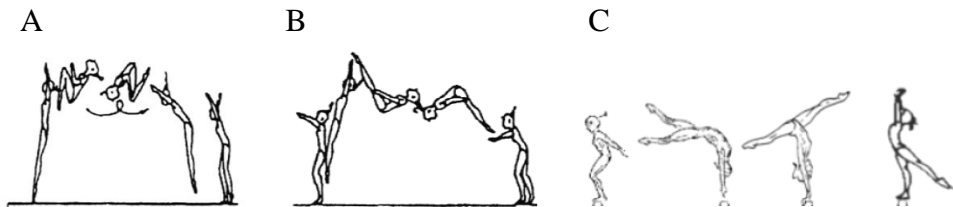
A   B   C

FIGURE 1. Analysed standing backward acrobatic elements with the flight phase: A – tucked somersault, B – piked somersault, C - handspring with landing in a place of takeoff; 2013-2016 Code of Points).

For comparison, the counter movement jump (CMJ) was selected, as it is similar in nature and structure to the takeoff.

The aim of the study was to evaluate the effectiveness of takeoff and changes in the mechanical motion parameters and bioelectrical muscle activity in selected *acrobatic elements with the flight phase*.

MATERIAL AND METHODS

SUBJECTS

Twelve healthy artistic gymnasts participated in this investigation. The participants were a convenient sample of highly competitive national standard female gymnasts who demonstrated proficiency in performing the skills required for the investigation. The gymnasts were informed about the nature of this study. Prior to data collection, they were required to sign a consent form which contained human subject regulations. Parent or guardian consent was required for those younger than 18 years old. The research project was approved by the Ethics Committee for Scientific Research at the Jerzy Kukuczka Academy of Physical Education, in Katowice, Poland.

All subjects were tested under the same conditions, in a laboratory setting. Each gymnast performed three randomised trials of four acrobatic skills: standing backward tucked somersault, standing backward picked somersault, standing backward handspring with landing in the place of takeoff , and vertical counter movement jump (CMJ). The rest periods between the jumps lasted about 3 min. In this study, the results of one of the participants were included and reported on. This participant was a woman gymnast with a body mass of 52 kg and body height of 161 cm.

METHODS

Using the SMART-E measuring system (BTS, Italy) a multidimensional registration of the motion was made. The system includes six infrared cameras with a frequency of 120 Hz, modules for wireless measurement of the bioelectrical activity of the muscle called Pocket EMG (BTS, Italy) and the KISTLER 9182C force platform (Switzerland).

The Smart Software (Smart Capture, Smart Tracker and Smart Analyzer) enables the spatial modeling (3D) and the calculation of mechanical parameters. Large spatial accuracy was achieved by attaching the test passive markers to the body of the research subject. The markers were placed in specific locations on both sides of the body allowing the overall center of the body mass to be determined. After the calibration of the system, the accuracy of the distance between two markers in 3D was 0,4 mm.

Before the performance of the exercises, the participant's skin was specially prepared where the mounting surface electrodes were to be located. The electrodes were placed where there was motor activation of the muscles (according to the direction of fibers, in accordance with European recommendations for surface electromyography – SENIAM). These electrodes were supposed to monitor the level of involvement of certain muscles (tibialis anterior, gastrocnemius (captur

mediale), rectus femoris, biceps femoris, rectus abdominis, gluteus maximus, erector spinae, deltoideus (pars anterior). All of the electrodes remained in the same place until the end of the second attempt. Electromyography signals were recorded using the Pocket EMG system with a sampling rate of 1kHz. The raw EMG signal was filtered (pass band Butterworth filter, 10-250 Hz). Next, the full-wave was rectified and smoothed using the root-mean-square (RMS) method with 100 ms mobile window.

The vertical and horizontal components of the ground reaction force were recorded and the force impulse of the takeoff phase and basic kinematic parameters were determined using MATLAB software. All of the measurements were synchronised in time by using the central processing unit.

This approach allowed the changes in movement within the kinematic and kinetic parameters to be analysed. It also gave an analysis of the level of muscle activity. The use of this modern measurement system has helped in the overall description of the techniques used in the standing acrobatic elements with the flight phase.

RESULTS AND DISCUSSION

Bearing in mind that biomechanics is concerned with the forces that act on the human body and the effects that these forces cause, the first place thing to be considered is the muscle action. Skeletal muscles are the primary actuator of the movement and are a real biological system designed to produce mechanical force and cause movement. Figure 2A and 2B shows the muscle activation characteristics (the so-called internal structure of movement; Król, 2003) of eight studied muscles. When considering muscle activity (activation) characteristics, a high amount of repeatability was found (Raczek et al., 1994). In the takeoff phase, there was an especially high amount of activity shown: anterior deltoideus, medial gastrocnemius, biceps femoris, erector spinae, and anterior tibialis. There was also an almost complete lack of activity the rectus abdominis during this phase.

The end of the flight phase increases the activity of almost all of the muscles in the tucked and piked somersault, with the exception of the deltoideus muscle. In the backward handspring, however, it was this muscle that was very active at the end of the flight phase. This is called pre-activation. According to many researchers (Avela et al.,1996; Gollhofer and Kyröläinen, 1991; Viitasalo et al., 1998), the timing and extent of this activation is at least a partly pre-programmed, learned response. "Higher centres in the central nervous system appear to be able to plan for expected stretch loads (feet hit the ground) by increasing muscle stiffness to anticipated optimums " (McNeal et al., 2007).
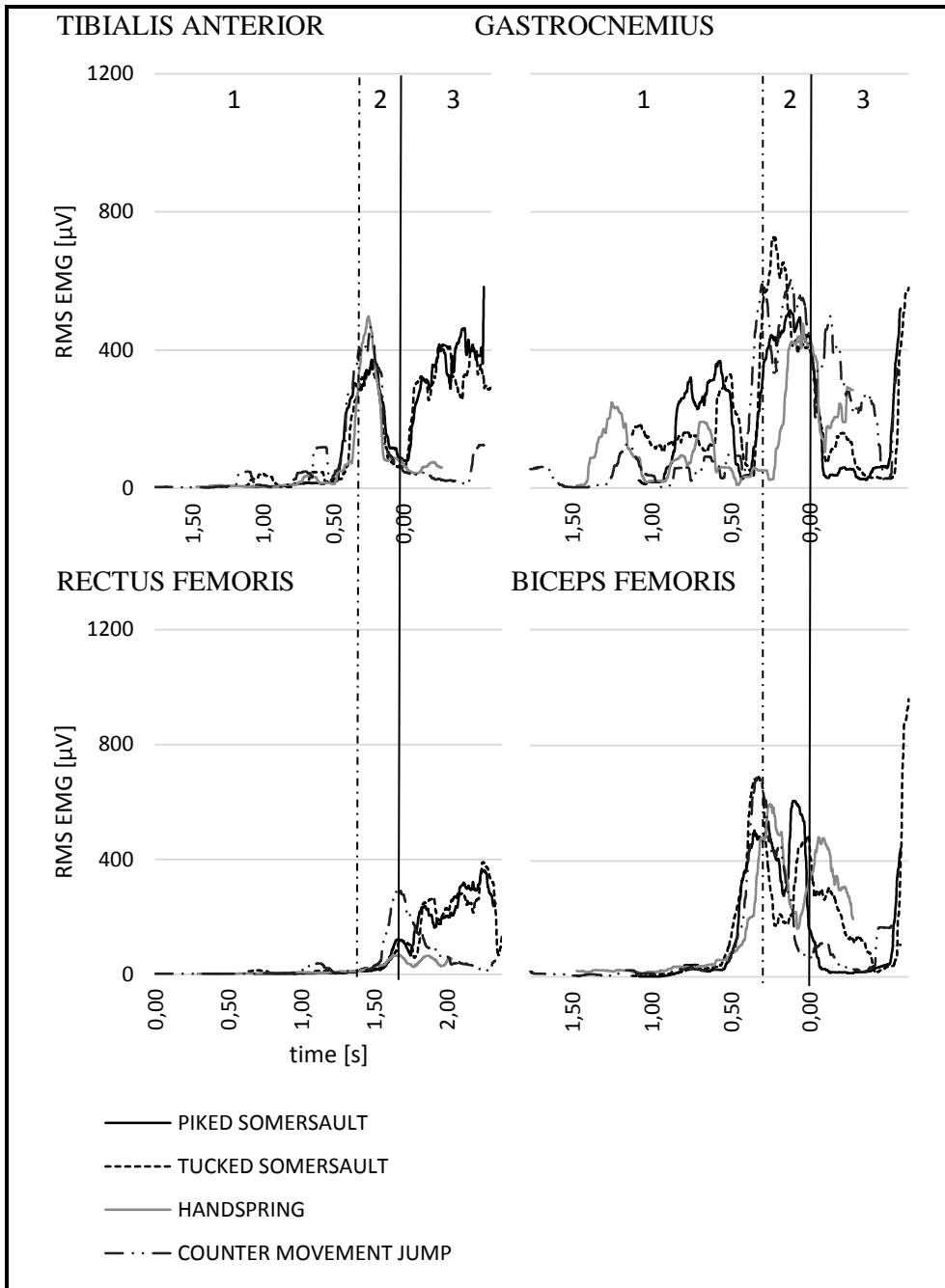
FIGURE 2. A) The Root Mean Square muscle activation (RMS EMG) of eight muscle in four acrobatic elements with the flight phase. All characteristics were adjusted to the end of the takeoff phase as a reference point. The vertical solid line marks the end of the takeoff phase and the vertical dashed line is the approximate beginning of the takeoff phase; 1– counter movement phase, 2 – takeoff phase, 3 – flight phase.
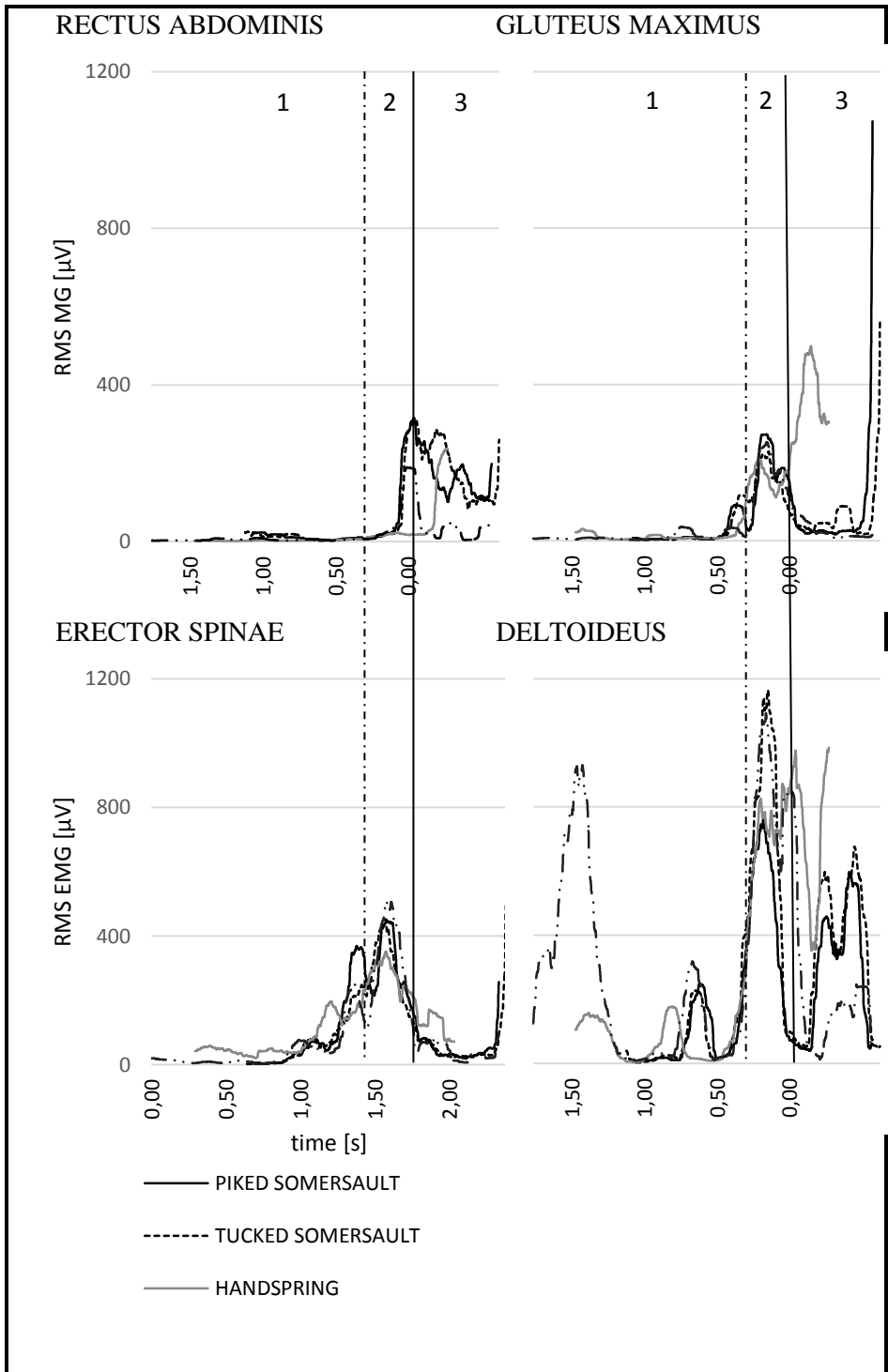
FIGURE 2 – (continued); B) - description same as for Figure 2 A.

The kinetic structure of movement (also called the dynamic structure of movement) of the analysed acrobatic elements with the flight phase reflect the records of the ground reaction forces, as shown in Figures 3 and 4. In principle, the records of the reaction forces appear visually to be similar in all four jumps. Only the vertical and the horizontal components of the reaction force during the handspring significantly differed from the characteristics of the remaining three jumps. This is both at the end of the counter movement phase as well as during the takeoff phase.
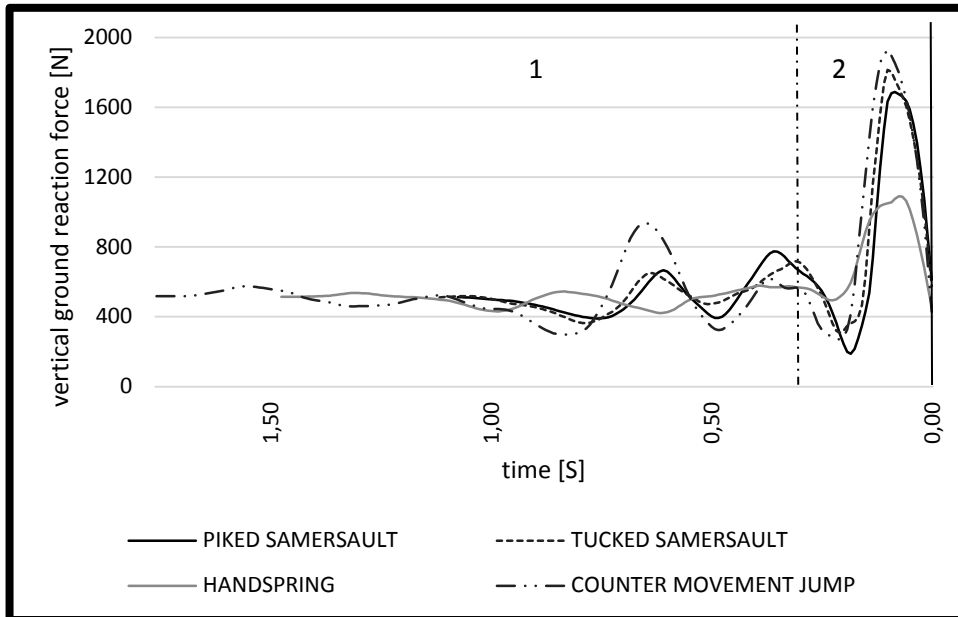

FIGURE 3. Vertical component of ground reaction forces in four acrobatic elements with the flight phase. All characteristics were adjusted to the end of the takeoff phase as a reference point. The vertical solid line marks the end of the takeoff phase and the vertical dashed line is the approximate beginning of the takeoff phase; 1– counter movement phase, 2 – takeoff phase.

Among the four acrobatic elements with the flight phase, the greatest vertical ground reaction force impulses were obtained in the takeoff phase of the counter movement jump (CMJ; Table 1; Figure 3).

Vertical ground reaction force impulses were much less in the tucked somersault (TS) and piked somersault (PS), respectively. The least amount of impulses were in the handspring with a landing in the place of the bounce (HS). Horizontal components of the ground reaction force impulse in these jumps were slight (Table 1; Figure 4).

TABLE 1. Mechanical parameters of four acrobatic elements with the flight phase

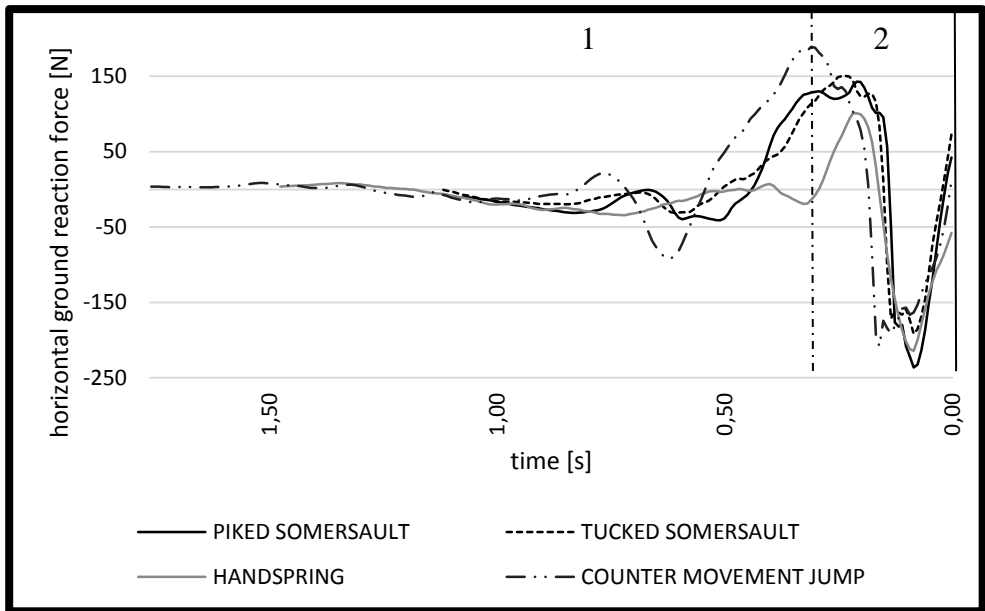| Acrobatic element Parameter	Counter movement jump	Handspring	Tucked somersault	Piked somersault
Vertical components				
Impulse [Ns]	143	74	127	105
Velocity [m/s]	2.74	1.41	2.43	2,00
Displacement [m]	0.38	0.10	0.30	0.20
Horizontal components				
Impulse [Ns]	8	3	4	2
Velocity [m/s]	0.15	0.06	0.07	0.03

FIGURE 4. Horizontal component of ground reaction forces in four acrobatic elements with the flight phase. All characteristics were adjusted to the end of the takeoff phase as a reference point. The vertical solid line marks the end of the takeoff phase and the vertical dashed line is the approximate beginning of the takeoff phase; 1– counter movement phase, 2 – takeoff phase.

The effects of the force impulses are the velocity of the body mass (COM) reached at the end of the takeoff phase, and the magnitude of the flight height. Of course, the obtained values of these parameters arrange themselves as in the case of the vertical impulse (Table 1). The highest magnitude of displacement and the velocity of COM was in the counter movement jump, and then in the tucked somersault, piked somersault, and handspring, respectively.

In our study, the obtained values of the COM vertical velocity are about twice as small as the Hraski (2002) data results. In Hraski's research, however, the

backward somersault was made after the typical acrobatic sequence: run up, roundoff, backward handspring, and the subject was a highly ranked, world-class gymnast.

According to Łukjan and Parlak (2005), the smaller magnitude of vertical velocity, and thus, the flight height in somersaults, compared with the counter movement jump, are affected by:

- shortening the displacement of the COM of the body during takeoff phase, resulting from a shallower squat,
- straightening (extension) of the hip precedes the straightening of the knee joints,
- incomplete knee joint extensions at the end of the takeoff phase,
- shortening the time of the takeoff phase. Commencement the takeoff phase from the extension of the hip joints before the knee joint extensions and incomplete knee joint extensions at the beginning of the flight phase of the somersault was also confirmed in our study (Figure 5). There were some differences, however, about the duration of the subsequent phases, which may result from the slightly different method of determining the beginning and end of the takeoff phase1. The temporal relationship of the successive phases (the rhythm of the movement; Król and Mynarski, 2005), as could be expected, was different for each of the jumps (Table 2).

TABLE 2. The phase durations for four phases of the acrobatic elements with the flight phase

Acrobatic element Phase	Counter movement jump	Handspring	Tucked somersault	Piked somersault
Counter movement [s]	1.508	1.108	0.825	0.825
Takeoff [s]	0.250	0.359	0.292	0.250
Flight (airborn) [s]	0.575	0.317	0.625	0.575

The angular momentum, is the second factor besides the vertical velocity of the COM, and tends to be reversed. The great magnitude of the vertical velocity in the backward tucked somersault corresponds to the small angular momentum, and the small magnitude of the vertical velocity in the backward piked somersault corresponds to the high angular momentum (Table 3). The magnitude of the angular momentum attributed to the COM at the takeoff phase was specified during the flight phase - immediately after the feet lose contact with the ground.

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[1] In our case, the beginning of the takeoff phase was accepted as the moment of the return of the movement in hip joints, after the counter movement phase. The end of this phase was accepted as the moment that the feet lose contact with the ground. In Łukjan and Parlak's article (2005) the probable beginning of the takeoff phase was at the lowest momentary location (position) of the COM at the end of the counter movement phase.

TABLE 3. Angular momentum and its components at the moment of the takeoff phase ends, for four acrobatic elements with the flight phase

Acrobatic element Parameter	Counter movement jump	Handspring	Tucked somersault	Piked somersault
Angular momentum [kgm^2/s]	*	**	43.6	58.8
Angular velocity [rad/s]	*	**	4.0	5.5
Inertia momentum [kgm^2]	*	**	10.9	10.7

* These data were not calculated because the movement was vertical

** No data for technical reasons

The angular momentum achieved by the gymnast in our research for the tucked somersault, was 43.6 kgm2/s, which was about 4.4 kgm2/s less than in the study by Łukjan and Parlak (2005). In the standing piked somersault, the gymnast achieved an angular momentum of about 10.82 kgm2/s greater than the athlete in the Łukjan and Parlak study (2005) in the tucked somersault.

In the article by Hwang et al. (1990), the magnitudes of the angular momentum were more than twice that of our results. In Hwang's study, however, seven top-class athletes performed the double somersault after a running start.

TABLE 4. The instantaneous position of the body's COM in four acrobatic elements with the flight phase

Acrobatic element Position	Counter movement jump	Hand spring	Tucked somersault	Piked somersault
Starting [m]	0.90	**	0.98	0.97
Squat at the end of the counter movement phase [m]	0.80	**	0.80	0.83
Beginning of the flight phase [m]	1.08	**	1.05	1.01
The highest of the flight phase [m]	1.45	**	1.34	1.24

** No data for technical reasons

The results of our study are consistent with Hraski's thesis (2002) that stated that greater angular momentum during the flight phase corresponds to greater horizontal velocity and smaller vertical velocity during the takeoff phase.

The kinetic effects can also be observed in the instantaneous positions of the COM (Table 4; Figure 6) or the relative angles of the joints (Figure 5).
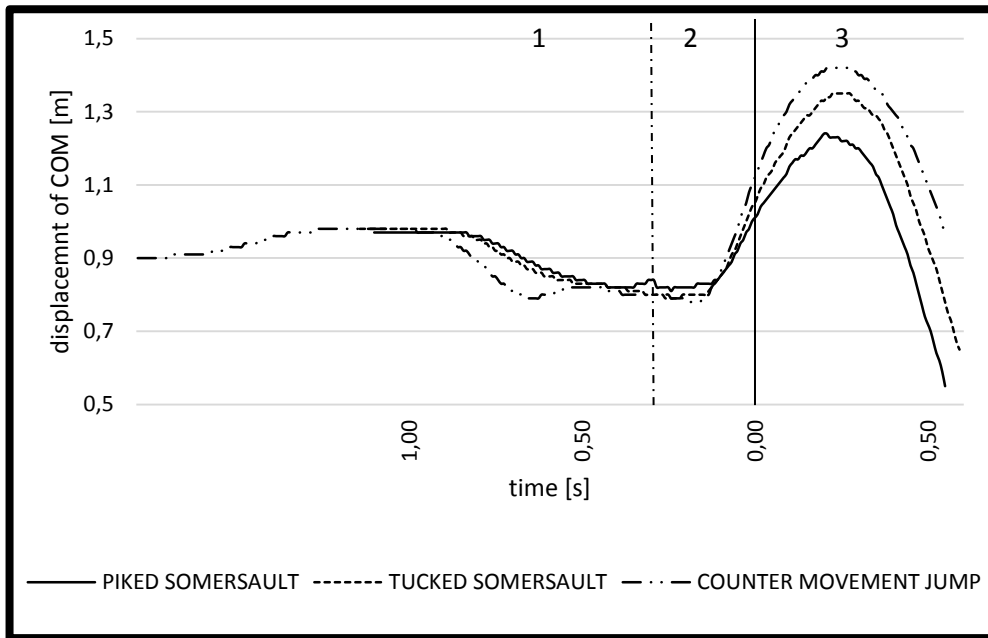
FIGURE 5. Relative joint angles for four acrobatic elements with the flight phase. Further clarification as in Figure 2.

The obtained values are confirmed data from the force platform (Table 1). The comparison of the standing backward somersault with the counter movement jump is of particular interest. As indicated in our article, the vertical velocity, and thus the flight height, conditional on magnitude of the force impulse, were higher in the counter movement jump.

The difference between the flight height in the counter movement jump and the standing somersault may be an indicator of the efficiency of the mechanism giving the angular momentum (Łukjan and Parlak, 2005). It can be assumed that the smaller the difference, the better the bounce to standing somersault. In this way, the mechanism giving the angular momentum, which follows from the similar takeoff nature in both forms of jumping, is known.

According Łukjan and Parlak, greater extension of the hip joints and less knee joint extension cause a greater rotational motion of the body in space. As recorded, an extension of the hip joints beginning earlier and carried out with higher velocity, cause a backward rotation of the body.
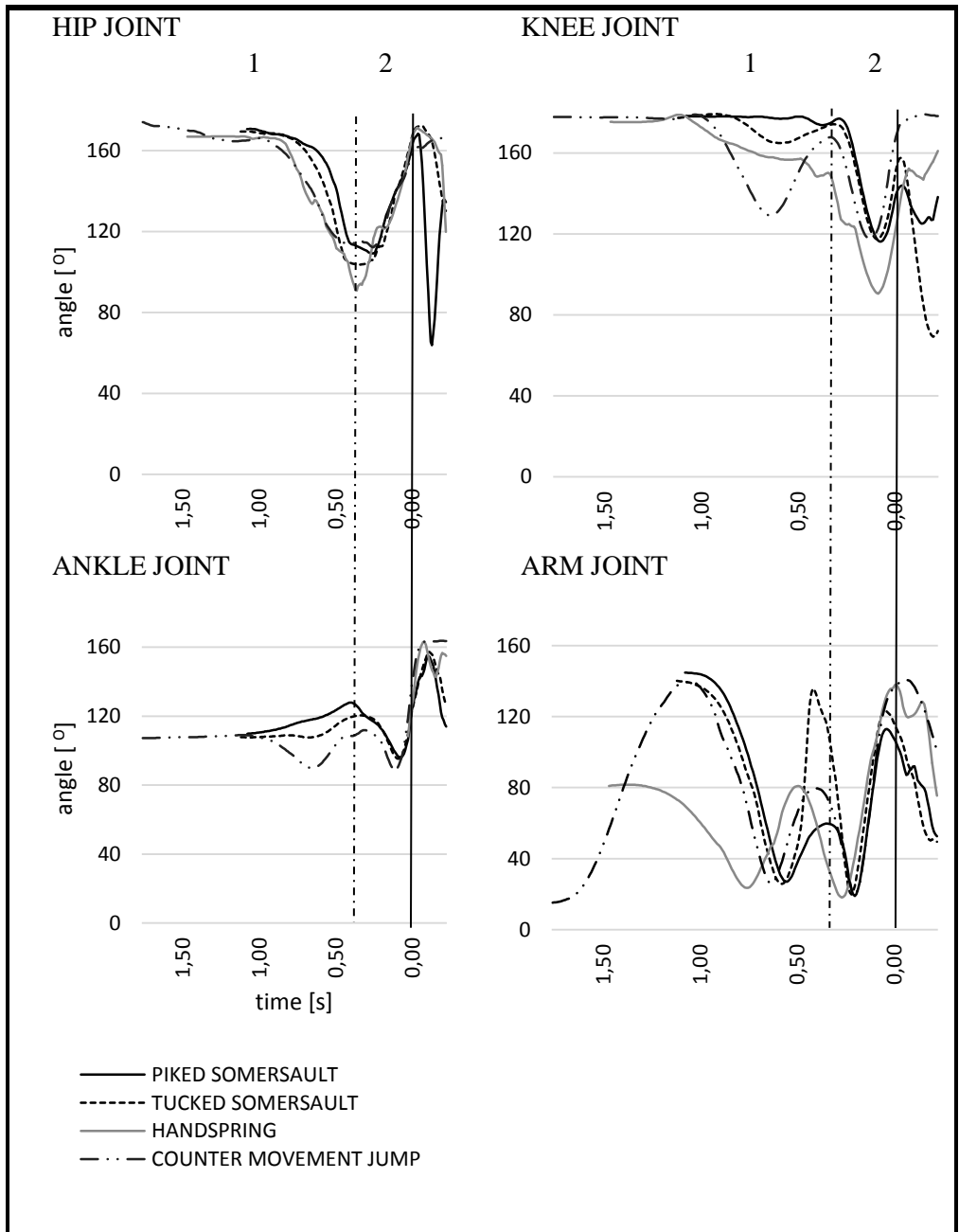
FIGURE 6. Vertical displacement of centre of mass (COM) of the body for three acrobatic elements with the flight phase (from technical reasons no data relating to backward handspring). All characteristics were adjusted to end of the takeoff phase as a reference point. The vertical solid line marks the end of the takeoff phase and the vertical dashed line is the approximate beginning of the takeoff phase; 1– counter movement phase, 2 – takeoff phase; 3 – flight phase.

The highest values of the angular momentum in the takeoff phase, is obtained by the parts of the body farthest from the ground, because they achieve the highest velocity. During the flight phase, the body parts which are the farthest from the ground will involve subsequent parts of the body and provide these body parts with angular momentum. The upper limbs, trunk, and head, which represent about 62% of the total body mass, play the main role in this mechanism.

In the case of a standing backward handspring where the landing is at the place of takeoff, some of the parameters were not possible to calculate for technical reasons. However, based on the available data from the force platform, it is known that the vertical force impulse, and the consequent vertical velocity, and thus the flight height, clearly differ from the values of these parameters in the other three jumps (Table 1; Figure 3). This also applies to the time of the movement phases. In the handspring, the takeoff phase is clearly longer, and the flight phase significantly shorter (almost two times shorter) compared with the somersault and the counter movement jump (Table 2).

CONCLUSIONS

1. In the takeoff phase of the acrobatic elements with the flight phase (jumps), the bioelectric activity of most of the examined muscle was greatest, compared with the counter movement phase and flight phase.
2. At the end of the flight phase, in the muscles with an eccentric action during the landing phase, there is a 'pre-activation' of the muscles, which is a kind of preparation for subsequent heavy loads.
3. An effective way of bouncing in the somersaults is characterised by having an appropriate angular momentum, with minimum loss of flight height.
4. The large angular momentum in the piked somersault as a result of bouncing, allows for a less vertical velocity of the body.
5. Better ability to use the principle of conservation of angular momentum in the tucked somersault compared to the piked somersault, allows for less angular momentum to be obtained during bouncing. At the same time the vertical velocity is greater.
6. Understanding the mechanism of bouncing can be used to improve the teaching methodology of the somersault.

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KINEMATIC ANALYSIS OF FLAT BENCH PRESS USING THE CLASSICAL TECHNIQUE AND IN A BENCH SHIRT

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Summary: This study attempts to analyze the biomechanical parameters of bench press while using the classical technique and while wearing a bench shirt performed by an athlete (aged 28 years with body mass of 72 kg and body height of 167 cm). The athlete performed a set of bench press repetitions at one repetition maximum (1RM) with maximal velocity at 50-100% of maximum mass (MM) using the classical technique (80-160 kg) and in a bench shirt (125-180 kg). Vertical displacement in a bench shirt was lower than without the shirt. Also observed was a better stability of the horizontal displacement during the descent phase (by 38%) and the ascent phase (by 43%). In addition, the study found a higher mean velocity in the ascent phase and a shorter duration of this phase. Using a bench shirt increased the lifted weight by 13%. Because the obtained results indicate that a change in the bench press technique occurred when a bench shirt was used, coaches should take into account that bench pressing with and without a bench shirt may require different movement loads.

Keywords: flat bench press, bench shirt, movement analysis, APAS

INTRODUCTION

Technique can be assessed by comparing the manner in which a participant performs a motor task to a model, that is, the best athlete in a given exercise. However, this only constitutes a visual comparison, one that is commonly used by athletes and coaches (Bober, 1992 and 2003). A barbell bench press is characterized by internal connections between various biomechanical parameters. Sports technique changes with the use of different supportive equipment. Due to the fact that most studies address the classical bench press and only a small number address the issue of bench pressing in a bench shirt (Silver et al., 2009), an attempt was made to analyze the kinematic structure of these two modes of flat bench press. Such analysis may provide more detailed insight into an athlete's technique. The aim of this study was carried out by comparing the course of changes in kinematic parameters, that is, displacement and vertical velocity, during the flat bench press.

MATERIAL AND METHODS

Video footage was recorded of a European-level Polish representative (second place at the European Championships). At the time of the experiment, the athlete's body mass amounted to 72 kg and his body height amounted to 167 cm. The athlete performed a set of single-repetition bench presses at maximal velocity and 50% to 100% of maximal mass (MM) using the classical technique (RAW) (80-160 kg) and from 70% of MM while wearing a bench shirt (SHIRT) (125-180 kg).

The experiment was conducted at the central laboratory of the University of Physical Education in Warsaw. Two Canon cameras with a frequency of 50 Hz, positioned 5 m from the testing site, were used to record the video footage. Markers were placed at the ends and in the middle of the barbell bar. The coordinates of marker positions allowed for a measurement of path and velocity. Computer analysis of the obtained data was performed using an APAS 2000 modular motion analyzer.
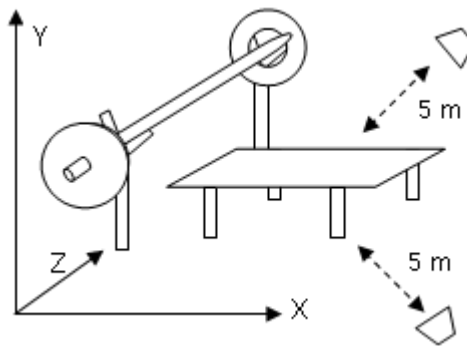

FIGURE 1. Scheme of measurements site.

The testing site (Figure1) comprised a free-standing exercise bench. The cameras were positioned at the side of the bench, rotated by an angle of 45°. The two cameras registered the entire testing site and the athlete.

Prior to the experiment, maximal mass (100% of MM) that the athlete was able to bench press with and without the use of a bench shirt was determined. The first set of bench presses was performed without the bench shirt. The set involved six single-repetition bench presses beginning at 50% of MM, with each subsequent press increasing by 10%, up to 100% of MM. Between each press, the athlete rested in an active manner (stretching and relaxing exercises) for 3 minutes. The second set of bench presses was performed with a bench shirt and began at a higher mass (70% of MM), which also increased by 10% with each subsequent press, up to the athlete's maximal strength capacity. As in the first set, the athlete rested in an active manner for 3 minutes between each press.

RESULTS

Based on the analysis of the obtained video footage, three phases of bench press were distinguished, according to the regulations of the International Powerlifting Federation (IPF) and according to Król and Gołaś (2009). Unracking and racking the barbell were omitted. The following phases of bench press were distinguished:

Phase I (the descent phase) began at the point where the athlete started to lower the barbell from locked elbows and ended when the barbell touched the athlete's chest (at the sternum).

Phase II (the halt phase) took place when then the athlete held the barbell on his chest without moving the barbell.

Phase III (the ascent phase) began when the athlete lifted the barbell from his chest and ended once he extended his arms completely.

Analysis of barbell displacement (D(y)) and vertical velocity (V(y)) during bench press at 100% of MM using the classical technique and with a bench shirt

Figure 2 shows the course of displacement (D(y)) and vertical velocity (V(y)) of the center of the barbell during all RAW presses (100% of MM) and SHIRT presses. Initial position of the barbell was lower when using the bench shirt. Barbell vertical displacement amounted to 30 cm during RAW presses (barbell weight = 140 kg) and to 28 cm during SHIRT presses (barbell weight = 165 kg). Halt time of the barbell equaled 0.7 s in RAW as well as SHIRT presses. The total time of a RAW repetition was higher by 7% (3.24 s) than the total time of a SHIRT repetition (3.0 s). Similar differences between Phases I and III were observed in terms of phase duration: phase duration was shorter during SHIRT presses (I: 1.0 s; III: 1.3 s) by 11% compared to RAW presses (I: 1.1 s; III: 1.4 s). During the final phase, the course of the D(y) line was more vertical during SHIRT presses than during RAW presses, due to a higher vertical velocity of the barbell.

Mean vertical velocity of the barbell in Phase I was similar in both modes (v_{mean} = 0.27±0.17 m/s). However, at the beginning of the phase, the highest descent velocity (v_{max} = 0.59 m/s) during RAW presses was observed that was 7% higher than the value achieved during SHIRT presses (v_{max} = 0.55 m/s). The velocity then decreased up to the point where the barbell stopped at the athlete's chest. Mean ascent velocity for maximal mass presses was 20% higher during SHIRT presses (v_{mean} = 0.25±0.08 m/s) than during RAW presses (v_{mean} = 0.21±0.09 m/s). The highest velocity (0.41 m/s) was registered during Phase III of SHIRT presses, which was 9% higher than maximal velocity in RAW presses (v_{max} = 0.38 m/s).

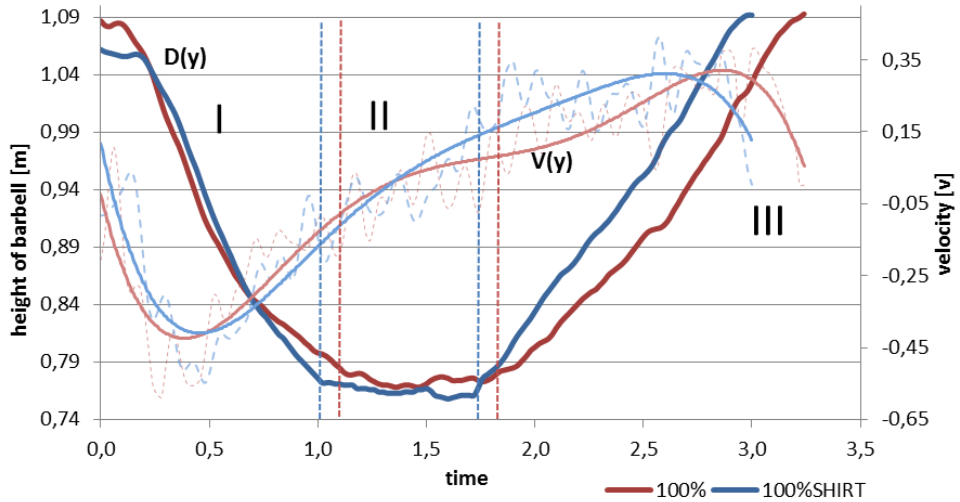**FIGURE 2.** Course of displacement D(y) and vertical velocity V(y) of the barbell in the descent phase (I), halt phase (II), ascent phase (III) ; 100% MM.
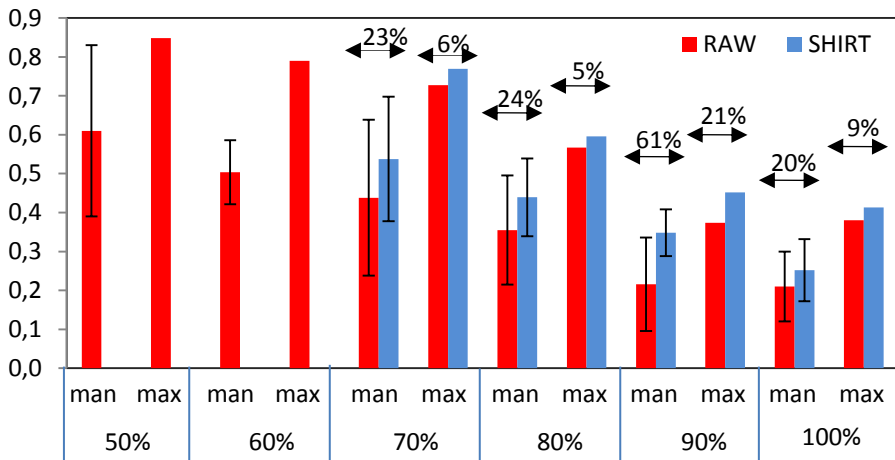

FIGURE 3. Mean and maximal values of velocity achieved for loads ranging from 50% to 100% of MM.

Figure 3 shows mean and maximal values of velocity achieved for loads ranging from 50% to 100% of MM. Presses within the 70-100% range were performed in both modes (RAW and SHIRT). Achieved values of maximal velocity decreased with the increase in barbell weight. The highest velocity during RAW presses at 50% of MM was 45% higher than at maximal barbell weight and amounted to 0.85 m/s. The greatest differences between maximal vertical velocity (21%) and mean vertical velocity (61%) occurred in the ascent phase at 90% of MM (RAW: $v_{max} = 0.37$ m/s, $v_{mean} = 0.22 \pm 0.12$ m/s; SHIRT: $v_{max} = 0.45$ m/s,

$v_{mean} = 0.34\pm0.06$ m/s). Maximal vertical velocity in the ascent phase during SHIRT presses at 70% of MM was similar to the velocity achieved in the same phase during RAW presses at 50% and 60% of MM. Similar values of percentage differences between SHIRT and RAW presses were observed for mean vertical velocity in the ascent phase at 70% and 80% of MM. Mean values of vertical velocity in the ascent phase at a given MM percentage were higher in all SHIRT presses than in RAW presses.

Analysis of barbell displacement (D(y)) and vertical velocity (V(y)) in bench presses with the same barbell weight during RAW and SHIRT presses

Initial height at which the barbell was positioned was 1.8 cm lower during SHIRT presses than RAW presses. The vertical displacement of the barbell amounted to 28 cm in the former mode and to 29.8 cm in the latter mode (Figure 4).
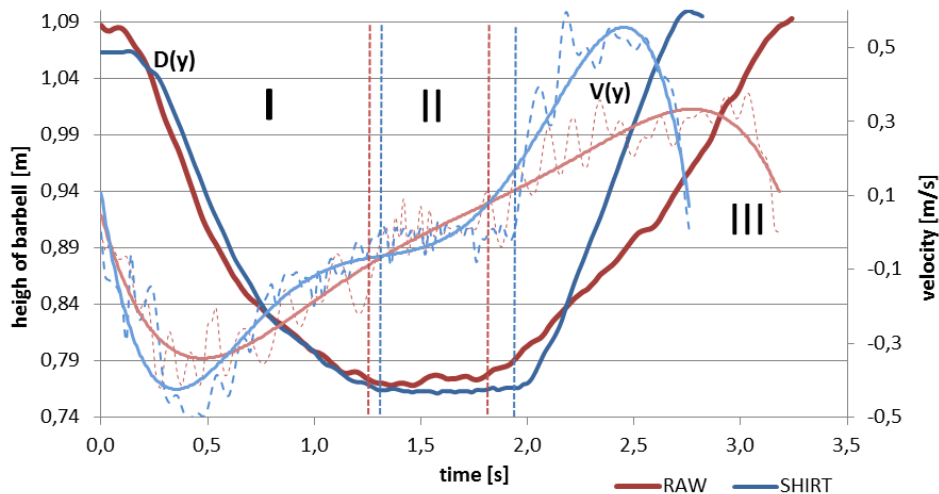

FIGURE 4. Course of displacement D(y) and vertical velocity V(y) of the barbell in the descent phase (I), halt phase (II), ascent phase (III) in case of the same barbell mass classic (RAW) and in bench shirt (SHIRT) condition.

In the initial descent phase during RAW presses, barbell velocity reached the value of $v_{mean} = 0.42$ m/s. The velocity then consistently decreased until the barbell stopped at the athlete's chest. Mean velocity in this phase amounted to $v_{mean} = 0.21\pm0.12$ m/s. Phase duration equaled 1.28 s. Halt time at the lowest position was 0.5 s. In Phase III, maximal velocity of the barbell was achieved toward the end of the press ($v_{max} = 0.37$ m/s), and mean velocity amounted to $v_{mean} = 0.23\pm0.10$ m/s. Phase duration equaled 1.44 s and the total duration of the press equaled 3.24 s.

In the descent phase during SHIRT presses, it was observed that the barbell achieved maximal velocity (0.51 m/s, which was 21% higher than during RAW

presses) much earlier. The velocity then decreased slightly more rapidly and over a slightly longer period than in RAW presses due to the bench shirt stretching under the weight of the barbell. The velocity decreased until the barbell stopped at the athlete's chest. Mean velocity in this phase was 12% lower ($v_{mean} = 0.19\pm0.58$ m/s) than during RAW presses, while phase duration was slightly longer (1.32 s). The athlete held the barbell at the lowest position for 0.64 s. The greatest differences in velocity occurred in the final phase. Owing to the bench shirt, the maximal velocity of the barbell was also achieved toward the end of the press, as in the other mode, and was 59% higher than in the other mode ($v_{max} = 0.6$ m/s). Similarly high values were observed for mean velocity in Phase III, where it was twice as high ($v_{mean} = 0.47\pm0.13$ m/s) than what the athlete achieved during RAW presses at his normal strength capacity. The ascent phase lasted 0.78 s and the entire press lasted 2.76 s.

Analysis of displacement in the sagittal and coronal planes during RAW and SHIRT bench presses using a barbell with the same weight
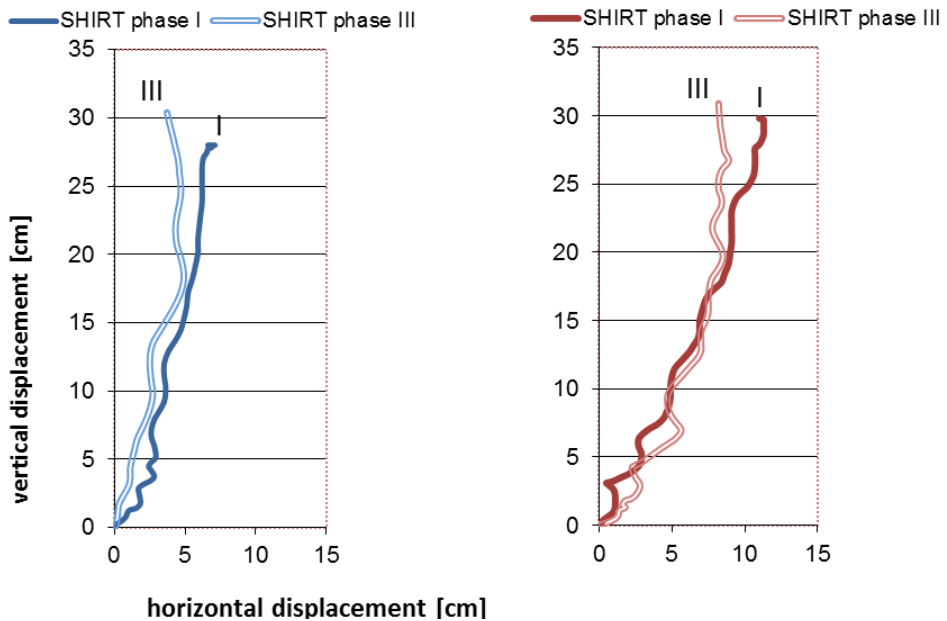

FIGURE 5. Trajectory of the barbell in the descent phase (I) and ascent phase (III) performed classic (RAW) and in the bench shirt (SHIRT) condition, subject A.

Because a bench shirt fits the athlete's body tightly, it limits the possibility to perform wide movements of the shoulder joints. This is why an attempt was made to analyze displacement in the sagittal and coronal planes during bench presses with a bench shirt and using the classical technique. Figure 5 shows the path of the barbell relative to the x- and y-axes.

In the descent phase (I), the spread of horizontal displacement of the barbell during RAW presses amounted to 11.3 cm; during SHIRT presses, barbell deviation from the vertical direction was 38% lower and amounted to 7.8 cm.

In the ascent phase, the path of the barbell was more vertical in both modes. However, the barbell showed greater horizontal stability during SHIRT presses. The athlete was able to lower maximal displacement by 43% down to $D(x) = 5.1$ cm during SHIRT presses compared to RAW presses, where maximal displacement equaled 8.9 cm.

Also analyzed was the lateral displacement (z-axis) of the barbell in the coronal plane (Figure 6).
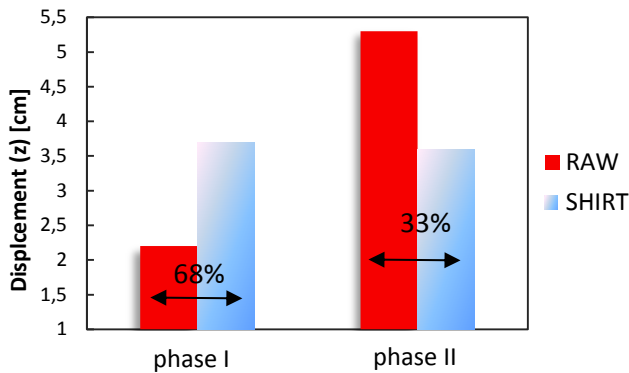

FIGURE 6. Displacement of the barbell (of the same mass) in the frontal performed classic (RAW) and in the bench shirt (SHIRT) condition, descent phase (I) and ascent phase (III).

The greatest differences occurred in the descent phase. Coronal displacement in this phase amounted to 3.7 cm during SHIRT presses. During RAW presses, the displacement did not exceed 2.2 cm. The opposite was observed in the ascent phase. During SHIRT presses, coronal stability of the barbell was higher, with lateral displacement amounting to 3.6 cm. During RAW presses, lateral displacement amounted to 5.3 cm.

DISCUSSION

This study attempted to analyze the kinematics of barbell movement in bench press using the classical method (RAW) and with a bench shirt (SHIRT). A detailed analysis of RAW and SHIRT presses allowed for changes in temporal proportions, spatial positions, and barbell velocity to be observed during presses performed in both of the aforementioned modes. A considerably longer descent phase as well as lower mean values of velocity were observed at 100% of MM during SHIRT presses, which may have been the result of the athlete's greater control over the significantly heavier barbell (the difference amounted to 20 kg)

during SHIRT presses. A greater maximal mass could have possibly been achieved during SHIRT presses had the bench shirt been new or fitted the athlete better.

On the other hand, when the same barbell weight was applied, the descent phase during SHIRT presses was only slightly longer than during RAW presses. This may have been caused by a considerable resistance exerted by the bench shirt. A high-quality bench shirt can increase performance by 20-30% or even more (www.prowriststraps.com, 2013).

During SHIRT presses, a lower initial position of the barbell was noted, which may have been caused by a severely limited movability of the shoulder joints that was applied in order to maintain better stability and greater tautness of the shirt in the chest area already from the beginning of the descent phase. The greater weight of the barbell also had a significant influence on the results.

During the ascent phase, the vertical velocity line showed a more dynamic path. In each bench press performed at 70-100% of the athlete's maximal capacity during both modes, the athlete achieved higher mean and momentary maximal values of velocity. It should be noted that during each SHIRT press, even though the same percentage of MM was applied, the weight of the barbell was higher than during RAW presses due to an ultimately higher weight being lifted that amounted to 100% of MM when the supportive equipment was used. Ascent phases during presses with the same percentage of MM were shorter. Differences that occurred in ascent phases during presses with the same load in both modes were found to be similar to those described above. However, it should be emphasized that mean and momentary values of velocity were much higher and ascent phases were considerably shorter during SHIRT presses. This was likely due to the athlete making use of the elasticity of the shirt, which allowed him to lift the barbell (i.e., to overcome its inertia) and accelerate it enough to finish the press with extended elbow joints. Thus, a greater velocity of the barbell resulted in a shorter ascent phase.

Analysis of spatial parameters during RAW and SHIRT presses with the same barbell weight showed that in both modes, a lower displacement relative to the x-axis occurred, which indicates that the path of the barbell was more vertical during the ascent phase than during the descent phase. However, when the bench shirt was used, displacement in the x-axis during the ascent phase and the descent phase was even lower. Perhaps the lower displacement of the barbell from the vertical direction was related to the stability of the shoulder joints, which were covered by the shirt. Different results were obtained for displacement in the z-axis. The descent phase during SHIRT presses showed a much lower stability in this axis. This may have been due to the way the shirt fitted the athlete, which prevented it from stretching under the weight of the barbell, especially toward the end of the

phase. If the shirt fits an athlete tightly, the athlete finds it more difficult to stretch it; as such, the barbell seems to "float" toward the side.

Available literature shows that analyses of kinematic parameters of flat bench press using the classical technique have already been conducted. Such assessments are useful for comparing the manner in which a study participant performs a motor task to a model, i.e., the best athlete at a similar level of skill. Król and Gołaś (2009) assessed the performance in flat bench press at 70-100% of MM (200 kg) of a World Champion with a body mass of 91 kg. Nawrat (2000) focused on comparing a group of 33 persons who did not train weightlifting with a group of 15 weightlifting athletes from the Academy of Physical Education in Katowice. The participants performed bench presses at 90-100% of their capacity. Non-athletes lifted an average weight of 64.7 kg, while athletes lifted 184 kg. Table 1 shows the duration of each bench press phase and Table 2 shows mean values of velocity achieved by the participants of Nawrat's study.

The technique employed by the athlete who participated in the study by Król and Gołaś (2009) was characterized by short durations of bench presses. However, it should be noted that he held the barbell at his chest for no longer than 0.18 s, while in this study, the corresponding times were much greater, ranging from 0.42 s to 0.8 s. Another author did not consider the halt phase at all, which means that study participants could perform the exercise with a swing technique, that is, they were able to employ their muscle activity cycle through extending and contracting their muscles. Such a technique allows athletes to lift a heavier barbell and, by bouncing it off their chest, give it a greater acceleration. Of course, using the swing technique at a powerlifting competition would result in a failed attempt. This study found that the descent phase at 100% of MM lasted shorter than the descent phase at lower barbell weights, similar as in the case of the athlete in the study by Król and Gołaś (2009).

Hamer (1999) observed even greater ascent velocities (0.85 m/s, Table 2); however, participants in Hamer's study performed a set of multiple repetitions with a much lower barbell weight. Students assessed by Nawrat (2001) also achieved a relatively high velocity (0.39 m/s) in bench press at 90-100% of MM. Nonetheless, it should be emphasized once again that the participants performed an acyclic movement that excluded the phase of isometric tensing of muscles when the barbell was held at the lowered position. In a study by Malisz (2001), participants with a much lower sports class were also able to lift barbells at near-maximum weight. They achieved a mean velocity of 0.31-0.36 m/s during the ascent phase, which was almost twice as high as the velocity obtained in this study. In a study presented by Kmiecik (2009), an athlete who belonged to the first sports class in powerlifting achieved a velocity of 0.32 m/s; this, however, was the maximal momentary velocity in the ascent phase, similar as in the case of a body builder of the same

class. Taking into account the near-maximal weight of the barbell (90-100% of MM), the results obtained in this study were the most similar to those obtained by Król and Gołaś (2009). The athlete achieved mean ascent velocities during SHIRT presses at near-maximal barbell weight (70-100%) that were each greater than those achieved by the World Champion from the study by Król and Gołaś using the classical technique. In contrast to powerlifters, weightlifters assessed by Król and Nawrat (1989) achieved very high barbell velocities. Ascent velocity of the barbell during presses at 90-100% of MM reached 2.05±0.08 m/s. However, the measurement of velocity was taken at a height of 74±3.1 cm.

Equally important in the assessment of flat bench press technique are spatial parameters that describe vertical and horizontal displacement. Table 3 shows data obtained by Silver et al. (2009) that pertain to performance in flat bench press with the use of bench shirt and without it. The assessment was conducted in a group of 5 participants aged 18-30 years with body height of 174.4±7.3 cm and body mass of 76.3±4.3 kg. The participants were asked to lift a barbell weighting 125% of their body mass, which in turn constituted 100% of their MM.

Silver et al. (2009) obtained significantly lower values of vertical displacement of the barbell during presses performed in a bench shirt. The authors also found a higher mean spread in the x-axis during presses performed in a bench shirt than without it. However, the mean value corresponds to both the ascent and the descent phase, which means that it is impossible to indicate the phase in which the spread was the highest. Even though the descent phase showed a higher spread, the path of the barbell was more linear. The differences between mean values of kinematic parameters obtained in our study may be the result of different measurement equipment and a different technique employed by the participants. The results may have been more useful for diagnosis had the study been conducted with a greater number of participants. In the best-case scenario, such an assessment should be conducted during a competition, which would create conditions beneficial for breaking records. Employing a three-dimensional analysis of the barbell path and kinematics of athletes' lower limbs and torsos would allow for a more detailed description of the mechanics of flat bench press technique using the classical method and with a bench shirt.

A bench shirt is only one of many types of powerlifting equipment. Sato (2012) analyzed another type of supportive equipment, that is, weightlifting shoes. He assessed kinematic parameters of barbell squat performed in sports shoes and in special weightlifting shoes. Sato observed significant differences in lower displacement of the torso during squats performed in the latter. However, does the use of bench shirts that allow an athlete to lift a barbell with increased weight that exceeds human natural strength capacity not harm the athlete's health? After all, a bench shirt does not cover all joints vertically strained by the weight of the barbell.

Therefore, it would be advantageous to conduct broader research in the future on not only the technique of bench press in a bench shirt, but also on the potential threats to the locomotor system that stem from the applied load.

CONCLUSIONS

The general aim of this study was to investigate the effect of using a bench shirt in flat bench press with increasing load. The following conclusion can be drawn from the obtained results:

1. Using a bench shirt results in:
   - a lower initial height at the beginning of the ascent phase,
   - higher mean and maximal velocity in the ascent phase,
   - higher stability of the horizontal displacement in the descent and ascent phases,
   - lower stability of the coronal displacement in the descent phase and higher stability of the coronal displacement in the ascent phase,
   - a prolonged Phase I, and
   - a shortened Phase III.
     Thus, kinematic parameters of the barbell movement improve, which benefits achieving better results during competitions.
2. The analysis of kinematic parameters showed that a change in the movement technique occurs when a bench shirt was used, forcing an athlete to develop his or her technical skills. This phenomenon stems from the fact that an athlete takes advantage of the elastic parts of the shirt, which may result in an increased value of the training load, necessitating an appropriate allocation of load constituents on the part of coaches.
3. Using a bench shirt allows for barriers of human physical capacity to be exceeded, as evidenced by the increased maximal barbell weight (by 13-25%) lifted by the participant of this study. This means that a shirt allows athletes to break records and build their psyche, as during competitions, they can successfully lift a barbell that weighs more than they would have been able to lift using the classical technique.

Based on the assessment of technique and barbell weight, it should be emphasized that the aforementioned technical preparation is indispensable, because an athlete's arms should be held wide during the descent phase to make the shirt stretch more. Conversely, strength preparation is needed to allow an athlete to lift the barbell at the point where the shirt no longer helps and the weight of the barbell is taken over by elbow joint extensors, which carry the load until the elbows are locked at the end of the bench press. The final necessary element is psychological preparation. Lifting heavy weights is extremely difficult and exerts strain on the

entire neuromuscular system. In addition, during the descent phase, an uncomfortable pain appears that results from the shirt pressing itself against the athlete's body. In such a situation, the athlete may develop a psychological barrier.

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BIOELECTRICAL ACTIVITY OF SELECTED MUSCLES OF UPPER LIMBS AFTER NEUROFEEDBACK-EEG TRAINING

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Abstract: The aim of the study was to assess the response of nervous and muscular systems of upper limbs in swimmers to training load with dynamic EEG Neurofeedback−. The study evaluated 3 swimmers (aged 20 to 22 years, body mass: 67-73 kg, body height: 178-182 cm). They participated in everyday training sessions in a swimming pool and additional 20 Neurofeedback training sessions−EEG in swimming ergometer VASA (3 times a week). We found a significant inter-individual variability in terms of surface EMG records (sEMG) in swimmer. The exercise evoked a submaximal work in the most of the muscles while it intensified local fatigue in others. A tendency for increased muscular endurance during final sEMG compared to the first test was found. Regular Neurofeedback EEG training on −swimming ergometer did not cause a disturbance in training cycle of the swimmers studied.

Keywords: sEMG, Neurofeedback− EEG, swimming training, upper limbs

INTRODUCTION

Swimming training might adopt a variety of forms, but it is always aimed at improving swimming quality and increasing the athlete's reserves of performance. Each stage of swimming training should involve carefully planned tasks to be implemented until participation in the major competition. Detailed plans help avoid haphazardness and organize the whole training process, thus increasing the likelihood of success in sport (Siewierski, 2010). There is no consensus among researchers on an unequivocal way to achieve these goals. Some researchers argue that more emphasis should be on technical training, while others increase intensity or strive for organizational and methodical optimization. Furthermore, there are researchers focused on a more specific dry-land training (Morouço, 2012) or on mental training to enhance control and competitive disposition (Sheard, Golby, 2006; Birrer, Morga, 2010; Ganter et al., 2007).

The objective of the dry-land training is more effective preparation of athletes for the load they are exposed to in water. Dry-land training helps improve swimmer's performance, reduce the risk of injuries and adapt to the conditions and stress typical of competitive settings. This also helps stimulate increasing the propelling force in water (Popovici, 2013). Its positive effect can be observed especially in a swimming sprint (Pichon et al., 1995), whereas Hoff et al. emphasized the substantial role of neural adaptations in improving work economy (Hoff, Gran, Helgerud, 2002). Other researchers demonstrated that swimming at maximum speed using ergometers to mimic the underwater phase of the stroke improves recruitment of motor units in muscles (Rouard et al., 1992). There are also critics of this form of training, including Tanaka et al., who argue that the best results can be achieved by performing strength exercises in water (Tanaka et al., 1993). One of the methods to supplement dry-land training is mental training. This type of training may adopt a variety of forms, such as motivation talks, personal development sessions and mental skills workshops (Goldsmith, 2010). Biofeedback is one of the advanced techniques which improve self-regulation. Biofeedback uses a computerized technique of feedback which analyses brainwaves (Neurofeedback−EEG) from different areas of brain and reverse stimulation at selected frequencies. Therefore, the method allows for control and improvement of the parameters observed (electrophysiological brain activity), which typically are not consciously controlled (Bar-Eli, 2002). Neurofeedback−EEG has been used for several years to improve performance in sport. Previous studies have demonstrated that this training helped athletes improve performance in their sports (Landers et al. (Kerick et al., 2004; Monastra, 2005; Hammond, 2005). It was shown, for instance, that Neurofeedback−EEG training used to enhance power of beta and sensory motor rhythm (SMR) in archers, gymnasts, ice skaters and skiers improves concentration of attention, reduces fears, improves control over emotions and motor coordination. In order to improve swimming performance, we decided to use Neurofeedback−EEG over the range of SMR, beta 1 and theta bands.

The main aim of the study was to evaluate bioelectrical activity in the muscular system of upper limbs in swimmers as a response to the training load with dynamic Neurofeedback−EEG.

MATERIAL AND METHOD

The study evaluated three swimmers− during the competitive mesocycle. The inclusion criterion in the study was lack of injuries in upper and lower limbs and neurological deficits. The athletes participated in everyday training sessions in a swimming pool and additional 20 Neurofeedback training sessions−EEG using VASA swimming ergometer (3 times a week). The study participants gave their written consent to participate in the experiment. All the procedures were approved

within a grant of the Ministry of Science and Higher Education in Poland. They were performed according to the standards of the Research Bioethics Commission of the University of Physical Education in Warsaw, Poland.

TABLE 1. Subjects

No.	Age	Sex	Body Height [cm]	Body Mass [kg]	BMI [kg/m²]
1	22	K	178	67	21.15
2	21	M	179	74	23.10
3	20	K	182	73	22.04

The examinations were carried out in the Interfaculty Laboratory of Neurophysiology. The data concerning anthropometric indices were collected in the Department of Physiology. Measurements of body mass and calculation of body mass index (BMI) used Tanita body mass analyser.

NEUROFEEDBACK–EEG TRAINING

The subject had electrodes attached to the head. The electrodes received bioelectrical signals from brain. During Neurofeedback–EEG training, the subjects were supposed to move the images on the screen so that four dolphins should be oriented towards the upper part of the screen (Fig. 1). Correct movement of the dolphins on the screen occurred when EEG signal received from electrodes C3 and C4 (in the system of 10-20) in the theta band (4−7 Hz) was reducing, whereas power of the SMR (12−15 Hz) and beta 1 (15−20 Hz) was increasing. The subjects repeated this training six times (5 minutes each) during a single training session. (30 minutes in total). In order to ensure the required change of the image on the screen, the reduction in the power of theta band and increasing the power of SMR/beta bands in subjects had to occur simultaneously (after 15 min. in C3 and 15 min. in C4). The subjects relaxed after each training session by closing their eyes for 30 seconds.
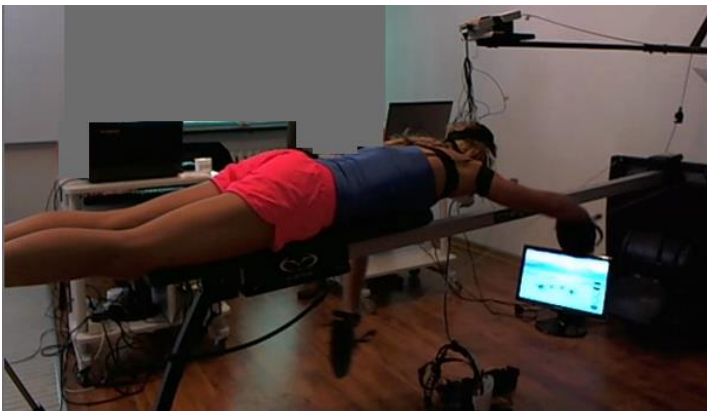

FIGURE 1. A swimmer during the test.

EMG/EEG TEST PROCEDURE

Measurements were performed before the first and after the last (20th) dynamic Neurofeedback–EEG training. Swimmers performed a front crawl stroke using a swimming ergometer at specific speeds, whereas lower limbs were supported relaxed on the attached platform. A mild reaction of the ground was used, with subjects lying prone. Each test took 25 minutes and was comprised of 4 stages. EEG signals and physiological parameters were recorded in prone position: 1. Relaxed (5 minutes), 2. During front crawl stroke performed by upper limbs at the rate of 24 pull-ups per minute (5 minutes), 3. During maximum exercise with front crawl stroke at the rate of 32 pull-ups per minutes (10 minutes), and 4. Lying prone, relaxed (5 minutes). Recording of sEMG parameters concerned two dynamic phases (2 and 3).

Parameters of the surface electromiography were recorded in m. trapezius pars descendens (TD), m. deltoideus pars acromialis (DA) and in the long head of m. biceps brachii (BB) in both upper limbs using Noraxon TeleMyo DTS apparatus. Double Ag/AgCL (Noraxon) electrodes were glued on the skin degreased with alcohol, parallel to the direction of tissues of the above muscles. Before the experiment, maximum strength was measured in TD, DA and BB, used in the analysis as a referential value. We employed MyoResearch (Noraxon) software to calculate the recorded sEMG signal. The examination was carried out based on Seniam standards. Raw sEMG signal was recorded at sampling frequency of 1500 Hz. Signal processing was performed at the frequency range of 20 to 500 Hz using Bandpass filter and – Hamming windowing.

RESULTS

The tables below illustrate the coefficient of simple regression for the amplitude and sEMG signal frequency in the first and final measurement during the warm-up and submaximum exercise and numerical and percentage values of the difference between these parameters. They were presented separately for DA, BB an TD muscles in upper right and left limbs.

Submaximal exercise was reached in the first swimmer, which was confirmed by the negative values of simple regression coefficient for both amplitude and frequency. The analysis of the differences between the first and the twentieth training session revealed a declining trend for this coefficient, which was particularly noticeable in the left upper limb.

The results obtained for the second swimmer showed negative values of simple regression coefficients, particularly in DA. More positive differences in this coefficient were observed during submaximal exercise compared to initial parameters.

TABLE 2. Simple regression coefficient for amplitude (A) and frequency (C) in the first (1) and final (2) measurements during the warm-up and proper exercise for the first swimmer and numerical and percentage differences between the measurements

Warm-up	A1 []	A2 []	C1[]	C2 []	A1-A2 []	C1-C2 []	A1-A2 [%]	C1-C2 [%]
DA p	-4.6	8.0	3.1	-0.7	12.6	-3.9	272.8	-123.0
DA l	13.3	-23.5	0.9	-0.9	-36.8	-1.8	-276.7	-196.2
BB p	-0.7	0.6	9.4	4.2	1.3	-5.2	178.6	-55.7
BB l	-0.1	-0.9	-0.2	-0.7	-0.8	-0.5	-644.9	-275.2
TD p	0.1	0.0	-0.3	-1.6	0.0	-1.3	-19.3	-382.4
TD l	-0.9	-0.2	-3.2	-1.4	0.6	1.8	73.7	57.0
Exercise								
DA p	-3.2	-0.3	-0.1	-0.6	2.9	-0.6	90.3	-706.2
DA l	0.1	-0.9	1.0	-1.6	-1.0	-2.6	-1926.0	-265.9
BB p	0.5	2.8	-0.5	-0.2	2.3	0.2	473.6	49.5
BB l	1.6	-1.1	1.2	-0.9	-2.7	-2.0	-170.7	-174.0
TD p	-1.4	5.2	-1.8	1.3	6.6	3.1	486.1	172.9
TD l	4.2	0.2	0.1	-0.1	-4.0	-0.2	-95.0	-195.1

TABLE 3. Simple regression coefficient for amplitude (A) and frequency (C) in the first (1) and final (2) measurements during the warm-up and proper exercise for the second swimmer and numerical and percentage differences between the measurements

Warm-up	A1 []	A2 []	C1[]	C2 []	A1-A2 []	C1-C2 []	A1-A2 [%]	C1-C2 [%]
DA p	-7.4	-2.2	-4.4	-4.1	5.3	0.3	70.9	6.7
DA l	-14.1	-7.3	-0.6	-7.3	6.9	-6.7	48.6	-1102.7
BB p	0.2	1.0	-3.1	-0.9	0.8	2.2	375.0	70.4
BB l	1.3	0.1	5.3	1.0	-1.2	-4.3	-95.0	-81.1
TD p	3.4	0.2	-0.5	0.6	-3.2	1.1	-94.9	211.9
TD l	-3.4	-0.9	-0.1	-4.9	2.5	-4.7	74.2	-3182.7
Exercise								
DA p	-1.2	0.4	-2.4	-2.6	1.6	-0.3	133.8	-11.5
DA l	-4.3	-0.2	-4.6	-1.3	4.1	3.3	95.8	72.2
BB p	0.6	2.0	-1.0	0.2	1.5	1.3	257.0	122.6
BB l	-0.5	-0.5	0.4	-2.3	-0.1	-2.8	-13.2	-662.0
TD p	-0.5	12.0	-3.1	-0.3	12.5	2.7	2532.9	88.7
TD l	0.5	0.9	-1.4	0.6	0.5	2.0	100.2	140.7

Based on the data obtained for the third swimmer, the highest decreases in simple regression coefficients were found for the biceps and left trapezius muscles. Similar pattern of changes was observed in the second subject during the exercise.

An increase in resistance to fatigue was recorded in part of muscles during final sEMG test compared to the first measurement, especially in left upper limb.

TABLE 4. Simple regression coefficient for amplitude (A) and frequency (C) in the first (1) and final (2) measurements during the warm-up and proper exercise for the third swimmer and numerical and percentage differences between the measurements

Warm-up	A1 []	A2 []	C1[]	C2 []	A1-A2 []	C1-C2 []	A1-A2 [%]	C1-C2 [%]
DA p	5.6	4.9	-1.7	-0.6	-0.6	1.2	-11.7	67.7
DA l	-5.2	3.5	-4.2	-1.6	8.7	2.5	167.3	60.8
BB p	0.4	3.9	-6.9	-4.8	3.5	2.0	862.5	29.6
BB l	-0.3	0.1	-1.5	-0.2	0.3	1.3	133.4	86.9
TD p	-18.2	0.3	0.01	-1.1	18.5	-1.1	101.7	-15121.4
TD l	13.5	0.0	-1.5	-1.2	-13.5	0.3	-100.1	18.3
Exercise								
DA p	15.7	-2.1	0.5	-1.2	-17.8	-1.7	-113.5	-357.1
DA l	-4.0	2.1	-6.8	1.1	6.1	7.9	152.1	116.7
BB p	0.4	-0.9	1.8	0.4	-1.3	-1.3	-301.8	-75.7
BB l	-0.7	0.3	-1.2	-0.1	1.1	1.2	144.2	94.1
TD p	1.3	3.1	-0.4	-1.3	1.9	-0.9	147.9	-221.1
TD l	-26.3	0.0	-1.9	-7.9	26.3	-5.9	100.1	-307.8

DISCUSSION AND CONCLUSIONS

Contemporary sport is undergoing dynamic changes. This is caused by incessant striving for beating records in the international competition and, consequently, continuous improvement in training methodology and comprehensive application of scientific and technological achievements. Platonow (1997) argues that, from the practical perspective, the opportunities for increasing training volume in order to improve performance in elite swimmers reached now the top limit, with swimmers already facing maximal training volume. Increasing the volume can be counterproductive i.e. lead to excessive utilization of adaptive biological reserves of an athlete (limitation of duration time of peak performance) rather than continuous improvement of competitive disposition. Other scientists have emphasized excessive use of training volume which helps athletes prepare to working at high level but is not reflected by performance during competitions (Costil et al., 1991, Brandon, 2002). Experts who have analysed swimming performance observed a tendency for increasing age span among peak results obtained by leaders in this sport. This involves elongation of time necessary for achievement of the highest sport skill level but also a relative increase in time of maintaining this level. Among the factors that make it possible to achieve and

maintain top performance at a champion level is mental state of an athlete (Opyrchał, Karpiński, Sachnowski, 2005).

In order to meet the demands of contemporary sport, scientists attempt to create comprehensive forms of training adapted to the needs. One of these disputable forms is training using swimming ergometer. Its effects are largely dependent on its specific nature (Delistraty, 1990). It is used by elite swimmers for diagnosis of the effects of swimming training. According to Popovici and Suciu (2013), training with ergometer should be performed with relation of 1h 45min to 3h of training in water. Four weeks of dry-land training significantly improve swimming speed at shorter distances (50m). Swimming ergometers are also useful for evaluation of individual achievements, with mechanical power (Heller, 2004) or capacity (Swaine, 1996) improved with the training. However, some researchers have criticized this form of exercise. They argue that this type of training might cause de-synchronization of swimming due to a unilateral breathing, which might intensify at the instant of reaching top muscular power (Potts, 2002). Furthermore, with reference to mental skill, these are trained as separated from physical, technical and tactical preparation. It is remarkable that the best outcomes are achieved if this training simulates competitive conditions (Goldsmish, 2010; Scurati et al., 2010).

The present study attempted to evaluate a combination of the effectiveness of training using swimming ergometer with Neurofeedback−EEG training. The results obtained are consistent with findings reported by other researchers (Aujouannet et al., 2006; Ganter et al., 2007), who have demonstrated that sEMG in swimmers exhibits a substantial individual variability. This might be correlated with the differences in the swimming style preferred and technique of swimming during measurements. The measurements showed that the exercise evoked a submaximal work in the most of the muscles while it intensified local fatigue in others. A manifestation which is likely to support this observation is a shift in sEMG signal towards lower frequencies after physical exercise, with the value of sEMG amplitue increasing (Farina et al., 2002). This phenomenon was observed by some authors both during isometric contraction and dynamic work (Ament et al., 1996). The literature has also reported on studies where no such changes were found (Arendt-Nielsen, Mills, 1985). At the initial stage of fatigue, a specific increase in sEMG signal amplitude during physical exercise can be observed (Gandevia, 2001). Activation of motor units is noticeable at this stage (Gates, Dingwell, 2008). In order to maintain the activity level necessary for performing a motor task, the central nervous system intensifies stimulation of the motor units. Consequently, this increases that number of discharges in active motor units and intensifies recruitment of previously non-involved motor units. Activation of the previously inactive units has, however, some limitations. The limitations are connected with the type of muscle, level of exercise-induced metabolites, and volume and intensity

of the physical exercise performed (Gandevia, 2001). When symptoms of fatigue are intensifying, the number of stimulated motor units is increasing − whereas the amplitude is decreasing (Farina et al., 2002). On the other hand, the changes in frequency observed in the study might reflect the status of activity in the muscular system in terms of readiness for performing a particular task. A tendency for increasing the muscle endurance can be observed during final sEMG test compared to the first measurement.

The results obtained in the study lead to the conclusion that regular dynamic Neurofeedback–EEG training did not cause a disturbance in training cycle in swimmers. The effects obtained cannot be isolated from all the activities performed by swimmers. Therefore, further studies should verify the effect of the above training on increasing the level of resistance of muscles to fatigue.

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STRATEGY OPTIMIZATION DURING RUNNING OVER VARIABLE SLOPE TRACE

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Abstract: The optimal strategy may be considered only for middle and long distance running. The athlete uses his maximal abilities during short distance events. Here, the reserves of energy are not depleted – there is no room for optimization. The optimal strategy running problem may be formulated in optimal control. The athlete's velocity, that varies with the distance, should be found. It minimizes the time of covering the distance. Two physical laws should be held: the Newton second law and an equation of energy balance. Such a problem has been considered many times by one of the authors of this paper. The new element of the current investigation is including the variable slope angle of the trace into the mathematical model of motion. The trace has been regarded as a straight horizontal line or as a straight line inclined at a constant angle up to now. Such simplification results from the limitations of the applied method – extremization method of linear integrals via Green's theorem. The method applied in the present approach is much more flexible. The fundamental conclusion of the paper is that the optimal velocity during the cruise is constant. The velocity does not depend on the local slope of the terrain.

Keywords: minimum-time running, Chebyshev pseudospectral method

INTRODUCTION

The minimum-time running problem is formulated in the following manner. The athlete should cover the given distance in minimum time. His velocity, variable with the distance, is not known "a priori". The runner varies his speed changing his propulsive force setting, that should belong to the given range. Using his maximal performance during the whole race is impossible because the energy staying at his disposal is limited. Different strategies may be employed during the event, but only one is optimal. The problem is a typical problem of optimal control or calculus of variations (Pinch, 1993).

The minimum-time running problem has been considered by many authors (Behncke, 1987; Cooper, 1990; Keller, 1973, 1974; Maroński, 1995, 1996; Pritchard, 1993; Woodside, 1991). The critical review of the solutions one can find in Maroński and Rogowski (2011). Most of them are based on an analytical considerations following the necessary conditions of optimality. The obvious shortcoming of such an approach is the simplicity of the mathematical models of running to be used. These methods, called indirect methods, are inefficient in numerical applications. Much more promising are so-called direct methods. Here all functions, variable with time, are represented by polynomials, and only the coefficients of these polynomials are optimized. The optimal control problem is converted into a nonlinear programming problem in such a way. The basic advantage of such an approach is flexibility of the problem formulation especially including the inequality constraints imposed on state and control variables.

MODEL

The modified Hill-Keller model of running is considered in this paper (Pritchard, 1993). The fundamental assumptions are:

- The athlete is represented as a particle. The variations of his center of mass position are low in comparison with the distance to be covered.
- The motion in vertical plane is considered.
- The runner's strategy is irrespective of the strategies of other competitors.
- The runner may change his velocity via variations of the propulsive force setting. The time of covering the distance is minimized.
- The profile of the trace is described by a known smooth function of the horizontal coordinate. Its local slope varies, and it is the fundamental difference in comparison with the solution given in Maroński and Rogowski (2011).
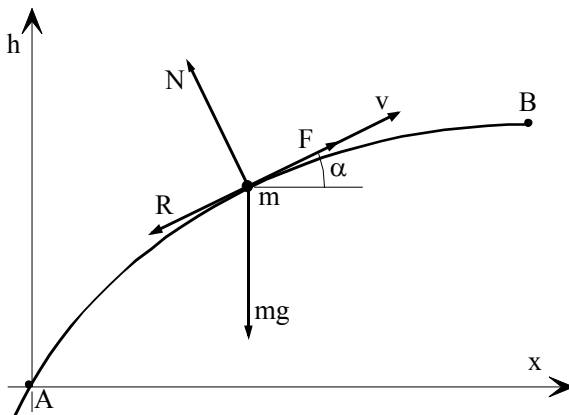

FIGURE 1. Forces exerted on the competitor. F is the propulsive force variable with the distance, $F = mf_{max}\eta$; R is the resistive force, $R = mr(v)$; N – the normal reaction of the ground; mg – the weighting force; α - the local slope angle; v – the velocity.

The mathematical model of running consists of differential equations – so-called state equations. The first one results from the Newton second law

$$\frac{dv}{dt} = f_{max}\, \eta - g\sin\alpha - r(v), \tag{1}$$

where: v is the runner's velocity, t – the time (independent variable), f_{max} – the maximal propulsive force per unit mass, η - the propulsive force setting varying with time (control variable), g – the gravitational acceleration, α - the local slope of the trace, r(v) – the resistance per unit mass

$$r(v) = \frac{v}{\tau}. \tag{2}$$

Here, according to Keller (1973,1974), the resistance is linearly dependent on the velocity v, and τ is an inversion of damping coefficient.

The energy conversion in the competitors body is given by the equation (cf. Behncke 1987; Keller, 1973, 1974)

$$\frac{dE}{dt} = \sigma - \frac{v\, f_{max}\, \eta}{e}, \tag{3}$$

where: E denotes the actual reserves of chemical energy per unit mass in excess of the non-running metabolism, σ – the recovery rate of chemical energy per unit mass, e – the efficiency of converting the chemical energy into mechanical one.

The above equations should be supplemented by kinematic equations

$$\frac{dx}{dt} = v\cos\alpha, \tag{4}$$

$$\frac{ds}{dt} = v, \tag{5}$$

where: x is the horizontal coordinate, and s is the actual distance measured along the given path h=h(x). Symbol h denotes the known smooth function describing the profile of the trace. Following equations are valid

$$\sin\alpha = \frac{dh/dx}{\sqrt{1 + (dh/dx)^2}}, \tag{6}$$

and

$$\cos\alpha = \frac{1}{\sqrt{1+(dh/dx)^2}} \; ,$$ (7)

where dh/dx is the derivative of the shape function. The state equations (1), (3), (4) and (5) should be supplemented by boundary conditions

$$v(0) = 0 \;, \quad E(0) = E_0 \;, \quad x(0) = 0 \;, \quad s(0) = 0 \;, \quad s(t_f) = s_f \;,$$ (8)

where s_f is the given distance to be covered, and t_f is the unknown time of covering the distance, and it is minimized

$$t_f = \int\limits_0^{t_f} dt \Rightarrow MIN.$$ (9)

Inequality constraints are imposed on the control variable

$$0 \le \eta(t) \le 1 \;,$$ (10)

and the state variables

$$v(t) \ge 0 \;, \quad E(t) \ge 0 \;.$$ (11)

Some explanations are necessary. In many publications referring to the dynamics of flight (cf. Panasz and Maroński, 2005), the flight path angle α is assumed to be low, then the component $(dh/dx)^2$ is low in comparison with unity. From equation (6) and (7) it follows

$$\sin\alpha \cong tg\alpha = \frac{dh}{dx} \;, \quad \cos\alpha \cong 1 \;.$$ (12)

Then, from equations (4) and (5), $x \cong s$ - the covered distance s is approximately equal to the horizontal coordinate x. In this paper however the assumption about low slope angle α is not valid because the behavior of the optimal solution for $\eta(t)=1$ is investigated. It means that the runner uses his maximal propulsive force on some segments of the distance where the local slope of the trace is high enough.

The formulated problem is solved applying the direct Chebyshev pseudospectral method (Fahroo and Ross, 2002). It employs the N-th degree Lagrange polynomials for state and control variables approximation. These variables at so-called Chebyshev-Gauss-Lobatto points are unknown parameters to be optimized in nonlinear programming problem. The *Optimization Toolbox* of MATLAB is used. The method is described in detail in Samoraj (2013).

RESULTS

The numerical method has been verified at first using the data of Keller (1973, 1974) and the results obtained by Maroński (1996). The specific values of such parameters as: E_0, e, f_{max}, τ, and σ cannot be measured easily in experimental way. They have been identified by fitting the results of the real events to the results obtained from the Hill-Keller model. Two events have been considered for numerical code verification – 400 m run and swimming over 100 m distance. The results have been satisfactory enough therefore the optimal strategies of running have been computed for different shapes of the trace and two distances: 400 m and 800 m. The results for 400 m run are more representative.
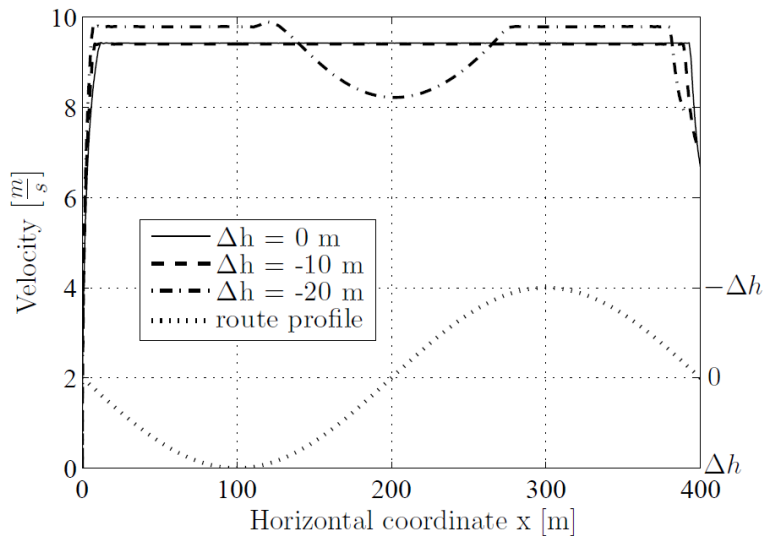

FIGURE 2. The optimal running velocities (*vertical axis*) for the trace described by function sinus having different amplitudes Δh (*bottom curve*). The horizontal axis is the horizontal coordinate of athlete's position x.

The optimal strategy consists of three phases: acceleration, cruise, and "negative kick" at the end (finish with decreasing velocity). Such property of the optimal strategy was known earlier. The optimal cruising velocity is constant for a straight line trace – horizontal or inclined. Current investigations show that it is also constant for variable but moderate slope

angles regardless of the local slope of terrain. The optimal cruising velocity decreases for high slope angles and running uphill when the constraint imposed on the propulsive force setting becomes active, $\eta(t)=1$ (Fig. 2). The athlete has no reserves to run with the constant velocity so he slows down.

CONCLUSIONS

The minimum-time running problem is reconsidered in the paper. The modified Hill-Keller model of running is employed. In the model, the athlete moves over the variable slope terrain. The fundamental result is that the optimal cruising velocity is constant regardless of the local slope of the terrain. If the inequality constraints are active however, the runner uses his maximal abilities and the velocity decreases.

According to Behncke (1987) and Keller (1973, 1974), in this model the efficiency e of transforming the chemical energy into the mechanical one is constant. A problem of minimization of energy expenditure during cycling over a given distance is considered in Maroński (2003). In his model of the exercise the efficiency e(v) is a function of rider's velocity. There, the optimal velocity is not constant even for low propulsive force settings, but these variations are relatively low. This should be investigated further.

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USE OF BIOMECHANICAL ANALYSIS FOR TECHNICAL TRAINING IN ARTISTIC GYMNASTICS USING THE EXAMPLE OF A BACK HANDSPRING

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Abstract This study had two aims. The first was to investigate the usefulness of the Kinovea computer programme in the assessment of artistic gymnastics technique. The second aim was to carry out a qualitative and quantitative assessment of technical errors by means of a frame-by-frame video analysis method as well as the analysis of selected kinematic parameters (using the example of a back handspring). The study comprised a champion class artistic gymnast. Technique for back handspring was analysed through a camera recording at a capture rate (frequency) of 120 Hz. Three artistic gymnastics trainers conducted qualitative analysis of movement technique using a frame-by-frame video analysis method. The authors of this paper used the Kinovea and SkillSpector computer programmes to carry out a quantitative assessment of errors that were indicated by the trainers. The trainers indicated four technical errors in the analysed back handspring. The first error was described as excessive forward bend of the torso in the first support phase on legs. The maximal angle determined between the torso and the vertical axis was 57°. The second error concerned knee joint flexion that occurred during the first flight phase in which the actual flexion angle was 58°. The third technical error was a forward leaning of the shoulders in the support phase on hands. The quantitative value of this error was 17°. The fourth technical error was defined as an excessive hip joint flexion in the second flight phase. Maximal hip joint flexion in this phase was 83°. Frame-by-frame video analysis allowed the trainers to identify four technical errors in the assessed exercise. No trainer ascribed the proper error value of knee joint flexion with regard to the existing regulations in artistic gymnastics. However, they correctly evaluated the error for forward leaning of the shoulders. The discrepancies between the trainers occurred in scoring errors related to excessive forward bend of the torso and excessive hip joint flexion.

This research shows that the Kinovea computer programme enabled the exact angle to be determined and, furthermore, that trainers can use the programme in assessing technique in artistic gymnastics.

Keywords: artistic gymnastics, check of technique, technique errors, biomechanics, back handspring

INTRODUCTION

Artistic gymnastics is a sport discipline where technical preparation plays a pivotal role on the way to mastery (Arkaev and Suchilin, 2004; Kochanowicz, 1998; Kochanowicz K., Kochanowicz A., 2010; Omorczyk et al., 2010). Therefore, one of the most important roles trainers play in this discipline is to lead the process of technical training connected with evaluating movement technique and indicating errors as gymnasts perform the elements (Sterkowicz et al., 2001). Based on their observation, trainers can only estimate the extent of error as a deviation from an ideal technique. It is not easy for trainers to precisely define the changes that occur in the movement technique that are influenced by improvements in training. This factor is significant when it comes to planning and verifying the process of sport training.

A special way to assess the efficiency of mastering a technique of gymnastics exercises is based on the results achieved in sport competitions. Scores given to gymnasts for their programs consist of several components: the difficulty of the program, the achievement of special requirements (drawn up by Panel D jury), and the value of errors (drawn up by Panel E jury) (FIG, 2013). Scoring, therefore, does not provide detailed information on the movement technique, such as indicating in which exercise and phase and to what extent the gymnast deviated from the ideal technique. Many times the accuracy of the final score for the performed program is distorted by different factors derived from the impossibility of indicating all errors, incorrect assessment of the location of body segments in relation to each other or to the exercise apparatus, and the intervention on the part of judges in the final score (placing some competitors at an advantage) (Ansorge and Scheer, 1998; Plessner and Schallies, 2005; Bucar-Pajek et al., 2011).

Trainers use different testing tools in assessing of the quality of selected gymnastic elements (among others, Duda et al., 2006; Kost et al., 2010). The results of the assessment of motor exercises obtained by observing a gymnast, which are similar to scores given during competition, are flawed mainly due to the imperfection of visual perception. Due to the structural complexity of artistic elements, the evaluation of a technique should be able to precisely locate errors indicated in specific phases of the exercise. This can facilitate the choice of appropriate forms of training that focus on eliminating errors. The indication of the

specific moment at which an error occurs can increase the pace at which artistic gymnasts process in technical training.

It has been demonstrated that cooperative work of practitioners and scientists of different fields, including biomechanics, significantly influenced improvements in artistic gymnastic technique (Jemni et al., 2011). Prassas et al. (2006) conducted a broad analysis of biochemical studies conducted with artistic gymnastics and discovered that trainers and scientists rarely cooperate to set up a joint investigation into explaining practical and scientific problems. The equipment used for conducting biomechanical measures and analyses can be effectively used for obtaining specific information about movement technique. The effective improvement of a technique requires trainers to use an individual approach with each gymnast (Czajkowski, 2005). This, however, significantly hinders the systematic use of biomechanical tools in practice. From the perspective of the trainer, this procedure of research and analysis is time-consuming and complicated. Therefore, trainers are still searching for tools that will easily provide them with detailed and objective information about the quality of the performed elements. A method that meets these requirements can be to record video of exercises at an increased capture rate and to use a computer programme that enables movement analysis.

The research presented in this paper was oriented to achieve two aims:

1. To investigate the applicability of the Kinovea computer programme to assess the technique of the performed elements.
2. To conduct qualitative and quantitative analysis of technical errors using a frame-by-frame video analysis method and to analyse selected kinematic parameters (using the example of a back handspring).

MATERIAL AND METHODS

The study participant was a champion class artistic gymnast. His was 22 years old, his body height was 1.73 metres, and his weight was 72 kilograms. The technique of a back handspring performed by the gymnast was assessed (Fig. 1). The start point was a position with straight arms overhead. Before springing from the legs the gymnast swung his arms. A back handspring was followed by an upward bounce and the element was finished by landing on both legs.
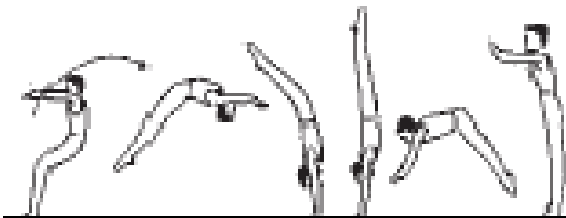

FIGURE 1. Back handspring (FIG, 2013).

The performed back handspring was recorded on video at a capture rate of 120 Hz (frames per second) using a Casio Exilim EX-FH25 digital camera placed on a tripod in a plane perpendicular to the direction of the gymnast's movement (from the side). Prior to recording, the gymnast had markers placed on the left side of his body with white elastic adhesive tape. The markers indicated the location of the selected axis of arm joints (the shoulder, elbow, and wrist joints) and leg joints (the hip, knee, and talocrural joints).

Three experienced artistic gymnastics trainers, who possessed authority to judge this discipline, independently conducted technical analysis of the gymnast's recorded movement. While analysing the frame-by-frame video recording, the trainers indicated technical errors in the analysed movement and compiled descriptive (qualitative) and point characteristics of the errors.

Descriptive characteristics concerned the description of the technical error in the protocol and indication of the moment (phase of the movement) in which it appeared. In order to facilitate the characterisation, the exercise was divided into seven phases: 1- the first support phase on the legs, 2 - first flight phase, 3 - support phase on the hands, 4 - second flight phase, 5 - the second support phase on the legs, 6 - flight phase, 7 - landing.

Point values of errors used for assessing the gymnast's movement technique were in accordance with judging regulations for artistic gymnastics and amounted to the following: small error = 0.1 error points, medium error = 0.3 error points, and large error = 0.5 error points (FIG, 2013). The scores given for each error were summed up and arithmetic means were calculated.

The trainers' analyses were typical assessments applied to movement technique during a gymnastics competition by Panel E jury. These aim at indicating errors in all phases of a movement. This is different from real-time assessment, as it is more precise due to the possibility of frame-by-frame and multiple video analyses.

The authors of this paper conducted quantitative analysis of errors indicated by the trainers. Using the Kinovea v.0.8.15 computer programme in selected frames allowed the angles between body segments to be determined. Moreover, the authors verified the previously determined angles via the SkillSpector v.1.3.0 computer programme. Using the provided body model, and after indicating the location of the markers (specific points on the gymnast's body) in individual frames, the timelines of selected kinematic parameters of the gymnast's body segments were calculated.

RESULTS

Table 1 shows both the descriptive characteristics of errors of the assessed back handspring and the point values noted by the trainers. They indicated four technical

errors in the first four phases of the analyzed movement. In the last three phases of the movement, they did not indicate any errors.

The error for forward leaning of the shoulders was given the same point value by all the trainers. In the other phases, the trainers were not unanimous in scoring technical errors. The trainers considered knee joint flexion and excessive hip joint flexion as the largest errors (in both cases, $\sum = 0.70$ points; $\overline{x} = 0.23$ points).

TABLE 1. Back handspring errors with point value (frame-by-frame analysis method)

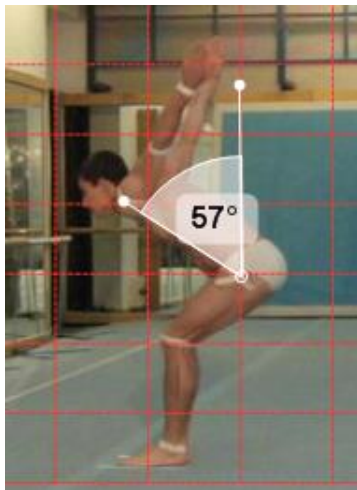| Movement technique error (descriptive characteristic)	Error point value				
	Trainer1 [points]	Trainer2 [points]	Trainer3 [points]	$\sum$ [points]	$\overline{x}$ [points]
Excessive forward bend of the torso – the first support phase on the legs	0.1	0	0.1	0.20	0.07
Knee joint flexion – first phase of the flight	0.3	0.3	0.1	0.70	0.23
Forward leaning of the shoulders – support phase on the hands	0.1	0.1	0.1	0.30	0.10
Excessive hip joint flexion – second phase of the flight	0.3	0.3	0.1	0.70	0.23

Figure 2 presents a method of determining angle via the Kinovea computer programme and the obtained angle between the torso and vertical axis (maximal forward bend of the torso). The same value (57°) was obtained through kinematic analysis by means of the SkillSpector computer programme (Fig. 3).

FIGURE 2. Forward bend of the torso - angle determined relatively to the vertical axis (Kinovea).

Figure 4 presents the method of determining the angle of maximal knee joint flexion in the first flight phase via the Kinovea computer programme. Compared to straight knees, the flexion angle was 58° (58° = 180° - 122°). A kinematic analysis carried out by means of the SkillSpector computer programme showed the same value (Fig. 5).
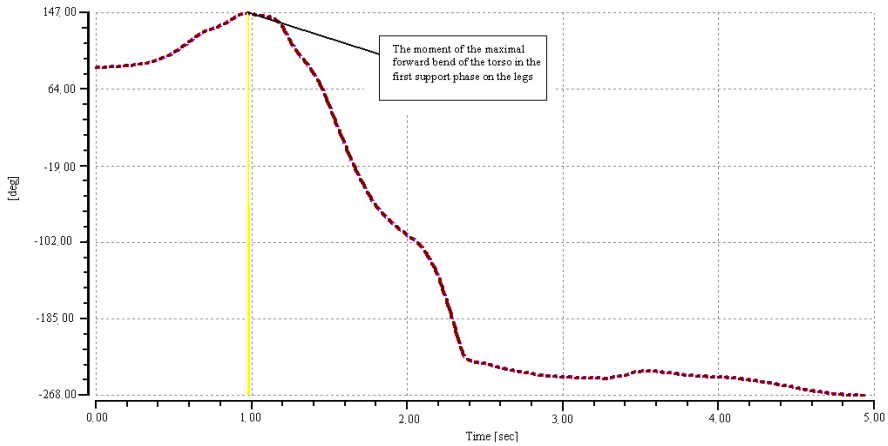
FIGURE 3. Angular changes of the torso in relation to the horizontal axis (SkillSpector).
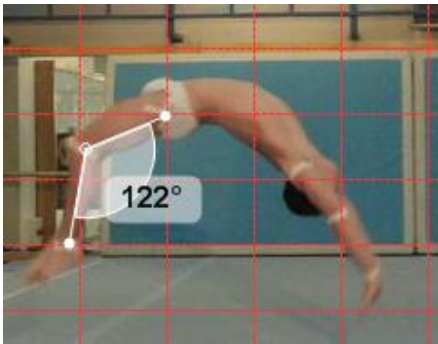

FIGURE 4. Knee joint flexion - the angle value was 58° (Kinovea).
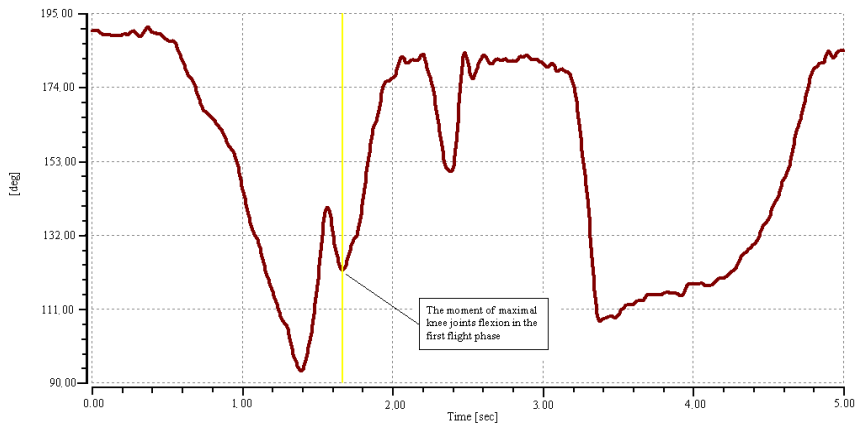

FIGURE 5. Angular changes of knee joint flexion (SkillSpector).

The shoulder joint flexion characterising in a quantitative way the forward leaning of the shoulders error was 17° (17° = 180° - 163°) in both the Kinovea

(Fig. 6) and SkillSpector computer programmes (Fig. 7). The shoulder joint flexion angle was determined for the frame in which legs were straight.
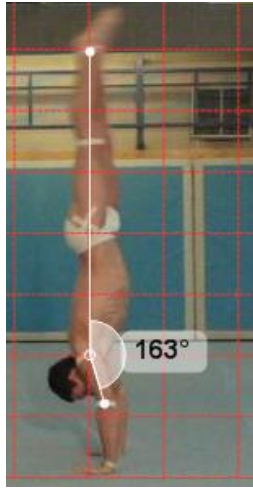

FIGURE 6. Forward leaning of the shoulders - shoulder joint flexion angle was 17° (Kinovea).
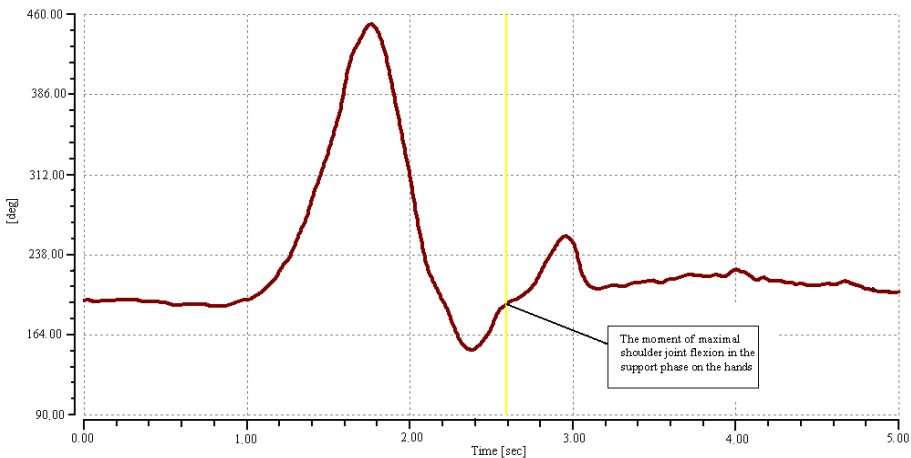

FIGURE 7. Angular changes of the shoulder joint flexion (SkillSpector).

Figure 8 shows the method of using the Kinovea computer programme to determine maximal hip joint flexion in the second flight phase. In relation to straight hip joints, the angle was 83° (83° = 180° - 97°). The same result was obtained in kinematic analysis by means of the SkillSpector computer programme (Fig. 9).
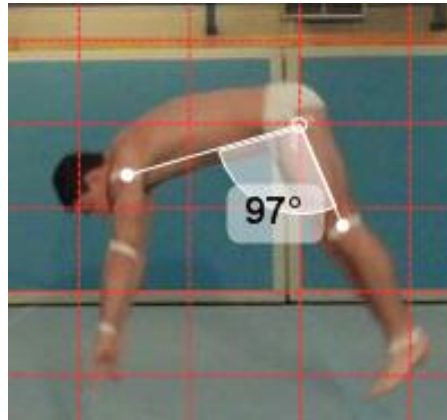
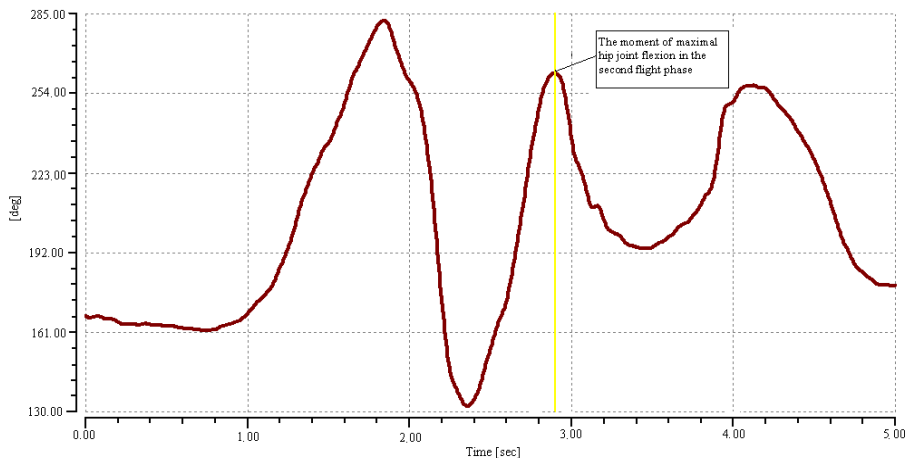**FIGURE 8.** Hip joint flexion - the angle was 83° (Kinovea).

FIGURE 9. Angular changes of hip joint flexion (SkillSpector).

DISCUSSION

The results of the research clearly demonstrated that qualitative assessment of artistic gymnastic technique based on movement observation should be supplemented with tools that provide quantitative data. The need to make use of quantitative data results from the fact that even analysis of video recorded at an increased capture rate did not contribute to trainers unanimously categorizing errors made by the artistic gymnast. The compliance of the results obtained from both the Kinovea and SkillSpector computer programmes demonstrated the possibility that trainers could use these two tools to assess technique in gymnastic elements. The aim of this paper was to show that the user-friendly and fast Kinovea computer programme can be used by trainers to more frequently check movement

technique (during systematic and operational controls[2]). The SkillSpector computer programme, on the other hand, is more complex, but provides more possibilities for movement analysis (or other programmes having similar options). The latter, then, can be used by trainers during less frequent assessment of movement technique (phased control[3]).

According to various authors (Jezierski and Rybicka, 2000; Kochanowicz and Karniewicz, 2002), the most frequent error in a back handspring performed from the position during the support phase on the legs is excessive forward bend of the torso. The data received on the basis of descriptive characteristics showed that two trainers identified this error and classified it as small. They argued that the 57° angle between the torso and the vertical axis exceeded the permitted value. However, it is difficult to correctly interpret this decision, as no written regulation has been made concerning the maximal or optimal angle value between the torso and the vertical axis in the described movement phase. Therefore, further research and analyses should be conducted that aims to establish the angle value of optimal hip joint flexion during the first support phase on legs. This would help to resolve ambiguity in describing the correct technique used in this phase of the exercise.

Based on the video recording, all the trainers indicated knee joint flexion error during the first flight phase. Two of them classified the error as medium (0.3 points); one of them classified the error as small (0.1 points). Biomechanical analysis and the Kinovea computer programme were used to determine that the angle of the flexion amounted to 58°. The results of a detailed biomechanical research carried out by Ambroży et al. (2010) with a champion class artistic gymnast showed knee joint flexion error in the same phase of the exercise. It can be assumed that knee joint flexion in the first flight phase of a back handspring facilitated the performance of this exercise. Perhaps in the following phase the gymnasts supported jumping from the hands by straightening the knee joints. It seems that this movement is performed by most of the technically advanced gymnasts, and it is impossible to indicate it in the real-time observation during the competition. This is due to the very short duration of this phase of the movement. Kochanowicz and Karniewicz (2002) observed that the time value of the first flight phase of back handspring (from a stationary position) performed by a championship artistic gymnast amounted to 0.205 seconds. Penitente et al. (2011) observed that the average time of the first flight phase of back handspring

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[2] Operational control - the aim is to determine certain fluctuations in the state of unpreparedness of the gymnast during a specific microcycle or mesocycle of the training. Systematic control - the aim is to immediately assess a gymnast's condition in a specific moment of time (i.e., after performing the exercise or after a specific training session).
[3] Phased control - check of the results achieved during the entire preparation phase of the gymnast (during half a year, a year, or four years) (Ljach, Witkowski, 2011).

performed after the round-off amounted to 0.27 seconds. The research comprised female artistic gymnasts of different skill levels.

According to the artistic gymnastics rules (FIG, 2013), the knee joint flexion error in the first flight phase indicated by the trainers should be classified as large (0.5 points), as it exceeded 45°. The aforementioned discrepancies in scoring given by the trainers showed that flexion value of selected joints determined solely on the basis of real-time observation can significantly differ from the actual value. Dallas et al. (2011) demonstrated that experienced artistic gymnastics judges had difficulty in correctly determining angles even in static exercises (they assessed the inverted cross on the rings). Thus, it appears advisable to support the video analysis of movement techniques, particularly the assessment of selected joints flexion, with suitable computer programmes.

In the support phase on the hands, the shoulder joints flexion, which amounted to 17°, was assessed as forward leaning of shoulder joints error. It is worth emphasizing that the judges gave the score according to judging regulations (FIG, 2013). In the case of the occurrence of such flexion in a dynamic exercise, the angle value oscillating between 16° and 30° should be classified as a small error.

The support phase on the hands was an object of scientific interest due to the possibility of wrist joint or elbow injuries caused by reaction force during the jump up to the hands. Sands and McNeal (2006) proposed a technique of placing the hands on the floor, the goal of which was not only to effectively absorb and bounce but also to protect the joints from injuries. The authors emphasized the need to turn the finger slightly inwards. Shoulder joint flexion was described as movement that dampens ground reaction force during the jump up to the hands (Davidson et al., 2005). Shoulder joint flexion movement seems indispensable when it comes to protecting the gymnast from injuries to the wrist, elbow and shoulder joints.

Through biomechanical analysis, the determined maximal flexion value of hip joints in the second flight phase was 83°. While assessing the movement technique of the gymnast, two trainers classified the flexion error as medium; one of them classified it as small. In the specialist literature concerning back handspring technique, no information could be found concerning the exact correct extent value of the flexion. Further research is necessary for determining optimal hip joint flexion in this movement phase. Based on this technical error, it is possible to examine the effect of negative transfer between the subsequent movement phases. It is probable that the indicated excessive forward leaning of the shoulders in the previous movement phase influenced the decrease in spring force from the hands; as a result, the second flight phase was low. In the final stage, the gymnast was forced to flex the hip joints. It is worth adding that low flight phase was listed as a recurring error that negatively influenced the quality of landing (Marinsek and Cuk, 2010).

In the context of the studies presented, it would be advisable to carry out a more precise assessment of techniques for gymnastics exercises (of different levels of difficulty) involved in the successive stages of gymnasts' technical formation. The possibility of obtaining more precise data not only requires applying an increased capture rate for video recording but supplementary information (e.g., the determination of angles between body segments) obtainable by means of computer programmes as well. Considering the fact that this research focused on studying the case of only one champion artistic gymnast who performed a back handspring only once, it would be necessary to conduct a broader study. Thus, it would be possible to obtain more precise data concerning the back handspring technique and, furthermore, to verify different opinions on the correct technique in the specialist literature.

CONCLUSION

1. Frame-by-frame video analysis enables trainers to indicate four technical errors in back handspring performed by a technically advanced artistic gymnast.
2. Trainers incorrectly ascribed proper values of knee joint flexion errors on the basis of the artistic gymnastics rules. They correctly indicated the forward leaning shoulder error of a lesser angle value.
3. Discrepancies in scores given by the trainers for errors related to excessive forward bend of the torso and excessive hip joint flexion.
4. Kinematic analysis of the back handspring conducted by means of the SkillSpector computer programme showed that Kinovea determines the exact angle value and can be used by trainers in a quantitative assessment of a movement technique as well as the errors made in gymnastics exercises.

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STABILOMETRIC PORTRAIT OF HANDSTAND TECHNIQUE

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Abstract. Body balance control in the handstand is one of the basic skills required in gymnastic sports as well as in other sports. The aim of **the paper** is to identify the extreme – weaker and better – levels of techniques of handstand on a stationary surface.

Material and method. The study was carried out on two gymnasts of shorter and longer experience of sport training, aged 19 and 24. The basic condition for selection of subjects for the study was skill at balancing during the handstand. Five 10-second attempts of handstand were made on two AccuSway (AMTI) force platforms, one platform under the left and one under the right upper limb. The center of pressure (COP) relocations in the time function were registered. The range of COP relocations in the lateral and anteroposterior direction and the speed of relocations of this point were calculated, together comprising a stabilographic portrait of the subjects in the performance of handstand.

Results. The stabilographic portrait of two gymnasts of different levels of training differs mainly in the magnitude of the range of stabilization of body deviations in the frontal plane. The more advanced gymnast uses a greater range for body stabilization in the handstand. An aspect that differs in the way of keeping balance in the handstand is the direction and the speed of work of upper limbs as well as asymmetry of the speed of hand impact on the surface in the less experienced gymnast and its lack in the more advanced gymnast.

Conclusion. Subtle differences in the technique of handstand concern the reactions to body deviations, mainly laterally, and asymmetry in activity of upper limbs in the less experienced gymnast.

Keywords: balance control, gymnasts, handstand, center of pressure

INTRODUCTION

Maintaining balance in an opposite position to the natural standing posture is required in such sports as gymnastics and diving, but it is also a component of general and specific physical capacity of many other sports. Considering that the human does not learn the handstand in the first years of his life, gaining mastery of it requires long-term specialist training. Some authors stress that in the inverted

position greater deviations than in a natural position occur (Slobounov et al. 1996). This may indicate that balance in the natural position is more trained than in the inverted position due to the requirements of our life. However, there is a lack of knowledge concerning the diagnostic aspects of keeping balance in the inverted position.

Independently of the space perception of the human body, the condition to retain the upright position is to limit the relocation of the center of the body mass in such a way that its elevational view falls on the stability area limited by the area of feet or hand support (Błaszczyk, 2004; Sobera et al., 2007). The handstand requires precise coordination of movements of individual segments of the motor system in the vertical (perpendicular) configuration towards the surface while minimizing movements in the main joints. During the handstand the gymnast adjusts the balance through changeable pressure on the surface (through movement in the radiocarpal joints). Thereby he assimilates his body to the single inverted pendulum (Golema, 2002) – in the radiocarpal joint – supported on the hand base (Sobera et al., 2007). In the handstand the adjustment of the body balance occurs through the change of hand pressure on the surface mainly in the antero-posterior direction (Sobera et al., 2007). Deviations of the center of gravity from vertical are compensated by the pressure of fingers and/or deflection in elbow joints (Slobounov and Newell, 1996) which is traditionally called the center of pressure (COP). The image of the relocation of this point on the ground plane in the time function comprises the stabilographic portrait of a given gymnast. One can assume that each gymnast, depending on the level of his training, is characterized by a specific stabilographic portrait of handstand.

In the conditions of sport competition, a noticeable (for the eye) range of body relocation during the handstand results in a decrease of the mark for the performance; so such a state is interpreted as a technical error of the performance. The above interpretation maybe based on the conviction that the visible body deviations from vertical are connected with the balance technique during the handstand. Therefore great differences in the training period and sport class of the gymnast should be visible in the stabilometric portrait of handstand.

The aim of the paper is to identify the extreme – better and weaker – levels of techniques of handstand on the fixed surface.

MATERIAL AND METHOD

The study was carried out on two persons A and B, aged 19 and 24, with the body mass of 60 kg and 64 kg, the body height of 1.60 m and1.75 m, and the training period in gymnastics of 3 and15years, respectively. The basic condition for the selection of subjects for the study was the skill to keep balance in the handstand for 10 seconds. Five 10-s attempts of handstand were performed on two AccuSway

(AMTI) force platforms, one platform under the left and one under the right upper limb. Before the study trial exercises were performed which aimed at determining the hand spacing on the platforms, marking their contour. Further attempts were performed with the same hand spacing on the platforms. The gymnasts arranged their hands on the platforms and entered the handstand in an optional way. After stabilizing the inverted position the data registration was started.

COP relocations were registered in time function (Fig. 1).The measurement was made at a sample rate of 100Hz.

Based on the course of the COP point in time function the relocation COP range in the lateral direction (COP X) and antero-posterior direction (COP Y) and the speed of relocations of this point were calculated, together comprising the stabilographic portrait of gymnasts in the performance of handstand. The distribution of these parameters was checked using the Shapiro–Wilk test for normality and it was found that despite the small number of repeats of the test (n=5 for each of the tested persons) these distributions fulfilled the normality condition. After determining the mean and standard deviations in the five attempts of the above-mentioned balance indicators the significance of differences between indicators of the appropriate limbs of both studied persons and between the left and the right limb of each studied person was checked.

The calculations of the balance indicators were performed using the BioAnalysis software, and the statistical analysis was performed using Statistica 11 software.

RESULTS

The exemplary registration of the COP point of the left and the right upper limb during the 10-shandstand performed by subjects A and B is presented in Fig. 1 and 2. The assessment of relocations of the COP point of subjects A and B (Fig. 1) shows that the differences in performance of handstand concern the COP relocations in the medio-lateral direction more than the antero-posterior direction.

The person with greater sport experience is characterized by a greater range of relocations of the pressure point in the lateral direction (Table 1). Subject B has on average the COP range of the left hand greater by 45% (p<0.0007) and by 20% for the right one (statistically non-significant difference) compared to subject A. In the antero-posterior direction the COP ranges are comparable and do not differentiate the sport level of the studied persons to such an extent. This fact may have a certain practical relevance because the range of relocations in the antero-posterior direction is 4-5 times greater than in the lateral direction, i.e. in the natural way, so the observer who is the judge perceives large relocations more easily than small ones.

The speed of COP relocations does not significantly differ between subjects A and B. The difference between the studied persons is that in subject A with a 3-year training period an asymmetry of performance of the left and right upper limb occurs which is not observed in the studied person with a 15-year training period (Table 1).

TABLE 1. Mean values for the range of COP relocations and COP speed for the left and right upper limb in the lateral direction (X) and anteroposterior direction (Y) in gymnasts with a 3-year training period (A) and 15-year training period (n=5)

	A		B	
	Left hand	Right hand	Left hand	Right hand
COP X range [cm]	1.23**±0.23	1.32±0.35	2.24**±0.41	1.67*±0.33
COP Y range [cm]	6.92±1.94	5.53±1.59	5.90±1.39	5.47±1.30
COP speed [cm/s]	12.99*±1.47	9.91*±0.95	12.24±1.70	10.87±1.54

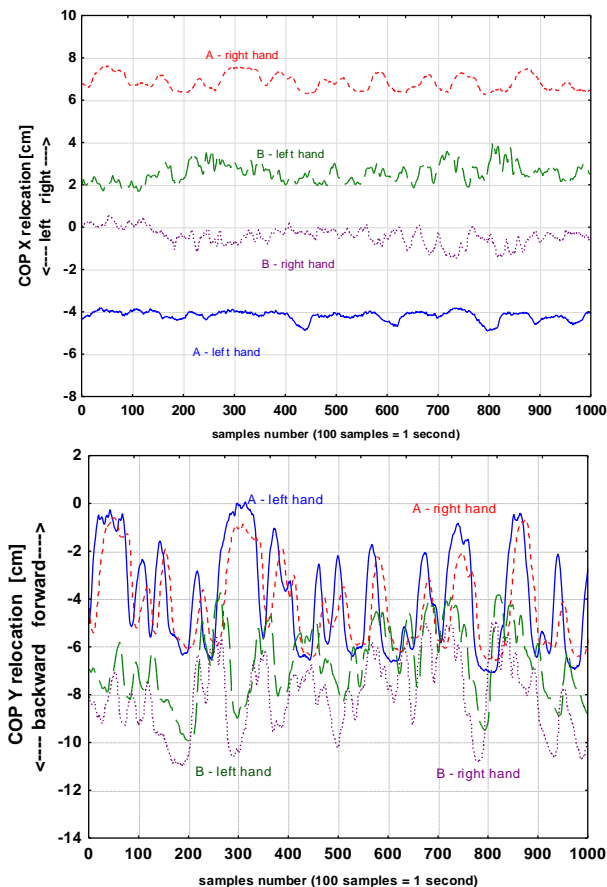*significant difference at the level $p<0.05$, **significant difference at the level $p<0.001$

FIGURE 1. Stabilographic portrait of gymnasts A and B – COP point relocations in the lateral direction (above chart) and anteroposterior direction (under chart).

In the case of both studied persons differences in value of some indicators of COP point between the left and right upper limb were noted. Gymnast A has significantly greater speed of COP relocations of the left upper limb than the right upper limb (p=0.002) (Table 1), and in gymnast B there is a significantly greater range of COP relocations of the left upper limb than the right upper limb in the lateral direction (p=0.02). The asymmetry of limbs is manifested in both gymnasts by greater activity of the left limb than the right one, although this concerns various indicators of body balance in the handstand. It is worth noting that the range of COP relocations in the antero-posterior direction does not differ between subjects A and B (Table 1, Fig. 1), which can be expected considering their sport advancement.

DISCUSSION

In the inverted position (handstand), the head with a significantly limited field of vision, the torso and the limbs are in an unnatural position. Uzunov (2008) stresses that proprioception and kinesthetic awareness have key significance in the handstand technique. Another concept was presented by Asseman et al. (2005), who pointed out the important role of the head position and visual control during performance of the handstand. A previous concept of balance was presented by Korienberg (1972), showing that the balance is more secure the more the deviation from the upright position can be eliminated and equalized. There are also such views that a greater amplitude of deviations around the body rest point means worse balance or worse performance of an equivalent task in a normal standing position (Kuczyński et al. 2012).

In this paper mean values of body balance indicators during the performance of a repeated 10-handstand were presented, considering two sport levels of the performers: weaker (represented by the gymnast with the 3-year training period) and better (represented by the gymnast with the 15-year training period). Similar results of COP relocations in the medio-lateral direction and antero-posterior direction were obtained by Croix et al. (2010).

The sport level of the studied persons does not significantly influence the magnitude of the range of COP relocations in the antero-posterior direction but the range of COP in the lateral direction is significantly greater in the gymnast with the longer training period than in the less experienced one, although this difference concerns only the left upper limb (Table 1). As a result, in the inverted position the adjustment of the body location occurs mainly in the lateral direction and has so far unknown significance. It may result from the fact that the gymnasts often perform handstands on an unstable surface such as parallel bars or rings on which the gymnast adjusts his handstand balance mainly through limiting the lateral movements of upper limbs. Such a surface requires additional stabilization of

relocation of center of body mass in all directions but the results of this paper indicate the lateral direction as the one in which the worse trained gymnast makes movements of a much smaller extent than the more advanced gymnast. There is also a view that the relocation of the center of the body mass takes place independently from the antero-posterior and lateral direction, and is responsible for the precision of the task performance (Balasubramaniam et al., 2000). Depending on the kind of task, these authors obtained greater swaying of the body in the lateral direction than in the antero-posterior direction in a normal standing position. The results of this paper are in compliance with the theory of the above-mentioned authors that the tendency for body swaying in both axes is necessary to keep balance in an upright position. If the participation of balance control is limited in one direction then the participation of balance control in another direction increases (Balasubramaniam et al., 2000). The gymnast in a handstand has a limited "area of operation" in the anteroposterior direction due to the relatively small longitudinal dimension of the hand (palm of hand) compared to the height of the center of body mass. The gymnast has greater possibilities for body bending in the frontal plane of movement (in the lateral direction). One can assume that the relatively small "area of operation" in the antero-posterior direction is compensated by a greater one in the lateral direction, although the assessment of the quality of performance of this exercise is based exactly on the body bending in the antero-posterior direction. From the theoretical point of view the lateral relocations of the COP point of the hand can be additional information steering the location of the body mass center or it can result from the greater muscular activity of the upper limbs performing a difficult task. Croix et al. (2010) registered a greater COP range by 48% in the lateral direction after closing the eyes during a handstand and only by 27% in the antero-posterior direction compared to a handstand with eyes open. Such a loss of the vision receptor caused greater disturbances in balance in the frontal plane of body movement than the sagittal plane.

Comparing the speed of COP relocations of both gymnasts one cannot explicitly state that they differ in the technique of handstand. The only significant difference concerns performance asymmetry of the left and right upper limb in the gymnast with the shorter training period than in one better trained, whereas the left limb showed significantly greater speed of COP relocation than the right limb. A similar tendency was noted in the more advanced gymnast but this asymmetry is not significant. The results of this study suggest that the left upper limb can react more quickly to the body deviation (is more active) and thus is responsible for the main function of stabilizing the inverted position. Better training of gymnast B than gymnast A is manifested among other things by the decrease of this asymmetry of functioning of the upper limbs during the handstand, which is in compliance with the aspirations of each coach in gymnastics. However, the asymmetry in function stabilizing the inverted position in the more advanced gymnast B is manifested by

the magnitude of the range of COP relocations in the lateral direction (Table 1). In this studied gymnast a significantly broader range of COP relocations in the lateral direction of the left upper limb than in the right one was noted, which was not observed in the less experienced gymnast. If the COP range and speed are matched, one can formulate a view that the more advanced gymnast can quickly react to body deviations in handstand and possesses a greater range of maneuverability (stability), in particular of the left upper limb. The less experienced gymnast reacts equally quickly to the changes in the body position but he possesses a significantly smaller area of hand stability in the handstand attempt, and also he struggles with asymmetric activity of the upper limbs by moving the body stabilization weight onto the left upper limb, unlike the more advanced gymnast, who can stabilize his body through the activity of both upper limbs.

Considering that both persons are sufficiently trained in keeping balance in the inverted position, the subtle differences in the performance technique concern the reaction to body deviations mainly in the lateral direction and the asymmetry in activity of upper limbs in the less advanced gymnast.

SUMMARY

The stabilographic portrait of two gymnasts with different levels of training differs mainly in the magnitudeof range of stabilization of body deviations in the frontal plane. The more advanced gymnast uses a broader range to stabilize his body in the handstand. There is a difference in the way of performing a task relying on maintaining balance in the inverted position shown by persons representing different sport levels. From the practical point of view there are certain mutual features in the way of maintaining balance, independently of the sport level. An aspect differentiating the way of maintaining balance in the opposite position to the natural one is the direction and the speed of action of upper limbs.

An additional aspect differentiating the sport level of the gymnasts is the asymmetry of the speed of hand impact on the surface in the inverted position in a less experienced gymnast and its lack in a more advanced one. However, it should be stressed that the presented results are preliminary and should be broadened to studies in a larger group of gymnasts.

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RELATIONSHIPS BETWEEN FUNCTIONAL LIMB MUSCLE STATUS AND SELECTED MOTOR EFFECTS OF BALLISTIC MOVEMENTS

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Abstract The first aim of the study was evaluation the levels of strength and speed of selected muscle groups in the elbow and knee joints. The second one was finding of correlations between the parameters of potential (laboratory examinations) and effective aspects of motor activity (throwing and kicking a ball). A group (n=30) of healthy students (aged 23-25) participated in the study. There were measured maximal moments of forces generated by the muscles and registered process of muscle force generation. Digital throw recording and ball kicking used camera. Maximum moments of forces in the muscles of the upper limbs in men were on average by 1.7 to 1.8 times higher than in women and 1.5 to 1.6 times higher than it was the case in lower limbs. Moreover, the highest values of the variables that characterizes the rate of force development we were always reported in men. The speed of the ball kicked was ca. 11 m/s (women) and ca. 13 m/s (men); in the case of throwing there were from 11 to 14 m/s and from 16 to 21 m/s (respectively women and man). We noted that maximum angular velocity in the flexion phase was lower than 10 rad/s, whereas in the phase of extension, it exceeded 18 rad/s. The maximum angular velocity in the knee joint (ωE) during throwing adopted the values ranging from 27 rad/s to ca. 40 rad/s. Results indicated only sporadic correlations between motor effects and static strength and speed abilities of the muscles. No significant correlations were found between the maximum rate of force development in static conditions, maximum rotational velocity in a joint during movement and maximum ball velocity.

Keywords: biomechanics, ballistic movement, ball throwing, ball kicking

INTRODUCTION

Function of skeletal muscles during natural human motor activity is based on the stretch-shortening cycle (SSC) (Bober et al. 2007). These researchers argued that the SSC helps increase force, velocity or mechanical power generated by muscles. The eccentric work of a muscle, which occurs before the phase of its shortening, is fundamental for the effectiveness of a variety of motor activities, both sport-related and functional. Examples of these activities are various punches, kicks and throws. There are also activities with very short performance times (usually below 0.3 s), termed ballistic movements (Morecki et al. 1971). Control of this type of movements is based on a simple feedback, which means that the correction is possible only after performing a specific movement. This control is termed ante factum (Morecki et al. 1971), because, due to a short duration time, the feedback mechanism that uses the stimuli to correct movements is not initiated. Furthermore, proprioception causes that a person, after performing this type of activity, is aware of its result (Bradley et al. 2007).

It seems that the effects of ballistic movements depend on the strength of the skeletal muscles and the rate of mobilization of muscle fibres. Strength-related human abilities are considered to be a manifestation of the abilities to overcome external resistance or to withstand them at the expense of the physical exercise (Sozański 1999). Furthermore, speed is considered as an ability to perform movements in the shortest time under the specific conditions (Sozański, 1999). Some authors have suggested that any physical exercise can be related to different points of the relationship between muscular force and the rate of muscle shortening (e.g. Osiński 2003).

The aims of the present study are focused around two problems. The first one is to evaluate the levels of biomechanical indices that characterize strength and speed of the groups of the muscles responsible for flexion and extension of the limbs in the elbow and knee joints. The second aim was evaluation of correlations between the parameters of potential (laboratory examinations) and effective (throwing and kicking a ball) aspects of motor activity. An additional aspect of the study was video recording of the motor activities performed so that the ball speed is maximum possible.

MATERIAL AND METHODS

A group of healthy male (n=15) and female (n=15) university students (aged 23 to 25 years) from the university course of physiotherapy in the University School of Physical Education in Krakow, Poland, participated in the study. All the participants were volunteers and were informed about the procedures and aims of the study and were aware of the possibility of stopping the experiment at any moment. An exclusion criterion was used for the measurements. The criterion was

participation in handball/football professional training sessions or participation in track and field training sessions.

Body height and mass ($\bar{x}\pm SD$) of the subjects were, respectively: 166.7 ± 6.1 cm and 57.4 ± 5.9 kg (women) and 180.3 ± 4.4 cm and 74.8 ± 8.1 kg (men). During the experiments, the subjects were wearing athletic clothes that did not restrict movements and athletic footwear. Before the examinations, each participant declared the preferred direction of laterality (i.e. handedness and footedness). The interview with the subjects revealed that all the participant were right-handed (right was the dominant hand). Furthermore, 1 woman and 3 men pointed to the left foot as a dominant one.

The study was carried out entirely in the laboratory of the Department of Biomechanics in the University School of Physical Education in Krakow, Poland, in two stages. The first stage evaluated basic morphological values and maximal moments of forces ($\mathbf{M_{max}}$) generated by the muscles that flex and extend the limbs in the elbow and knee joints under isometric conditions. Force generation in the muscles studied $\mathbf{F=f(t)}$ were recorded under the same measurement conditions. The second stage of the study involved digital camera recording of throwing and kicking the ball.

Dynamometric measurements were performed in the previously used positions (Staszkiewicz 2013), with the positions of the adjacent body parts so that the angles between the long axes of the forearms and arm and between the long axes of the thighs and lower legs were right. It was found that the length of the arm of the external force for the measurements in the area of the upper limbs was 0.22 m, whereas for the lower limbs, this value was 0.27 m. Each test of M_{max} was performed by the subjects twice and only the higher scores were archived. The changes of F=f(t) during the maximum generation of muscular force were also recorded twice (for each muscle group), but arithmetic means of each variable measured in both samples were adopted for further analyses.

The following indices were used to describe the rate of changes in the muscular force: $\mathbf{t_{Fmax}}$ (time to reach peak force), $\mathbf{t_{0.5Fmax}}$ (time to reach half peak force), $\mathbf{F'_{max}}$ (maximum value of the derivative of force with respect to time).

Hottinger (V9B) force transmitter with measurement range linearity of 2 kN was employed in the measurement line used for the above dynamometric tests. Furthermore, all the tests were recorded and subjected to analysis using AAD 4P software.

Digital throw recording and ball kicking used Casio Exilim EX-FH25 camera. The camera meets all the criteria and requirements for the equipment dedicated to this type of recording. Recording time was not longer than 3 seconds, although the movement recorded was much shorter. The videos were recorded at the frame rate of 120 frames per second, with the resolution of 640x480 pixels and shutter opening time 1/800 s. The above recording parameters help avoid smudging that

occurs during individual body movements. The camera was fixed on a levelled tripod and its optical axis and the direction of motion of the object recorded were perpendicular to each other. In order to ensure the best possible quality of video recording, the set was illuminated with two photographic lamps with power of 1000 W each.

In order for the motion of the recorded subjects to be processed digitally, markers made of white adhesive tape were attached in the characteristic locations on the skin. On the upper limb, these locations included: the acromion, the epicondyle of humerus, the radiocarpal joint space. In the lower limb: the greater trochanter of the femur, the knee joint space over the head of the fibula and the lateral malleolus. The marking of the above points was carried out by the same trained person. Selection of these points was determined by the need for using a mathematical model developed according to the pattern of the creators of the SkillSpector software that used the modules analysed in this software. This was a four-point model, with three of them being the above anatomical locations in the limbs that determined the axes of the joint and its two arms, whereas the fourth point was provided by the geometrical centre of the ball. This helped model the movements in the knee and elbow joints as well as the motion of the ball. Based on the videos recorded and using the model developed with the SkillSpector v.1.3.2 software, the following parameters were evaluated: the maximum horizontal velocity during the flight phase (v_B) and maximum value of the angular velocity for the elbow joint (ωE) and knee joint (ωK) in the sagittal plane using the global system of reference. ωE and ωK were determined for the two phases of movement: the preparatory phase (flexion of the limbs in the joints) and the throw phase (limb extension).
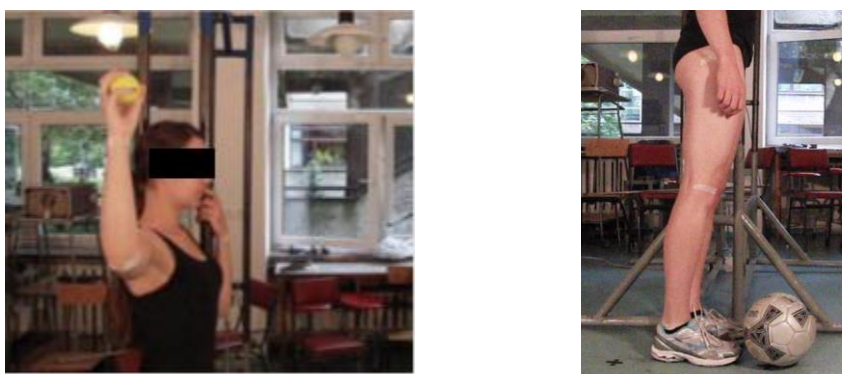

FIGURE 1. Initial positions used during recording of ball throwing and kicking.

The throws were performed using a standard tennis ball, whereas a football was used for kicking tests. Their masses on the day of measurements were 57 g and 440 g, respectively. The main recording was preceded with a short, individual warm-

up. Each type of the test (throwing with the right and left hand and kicking with the right and left foot) were performed and recorded twice. Similar initial positions with additional stabilization of the body trunk were used for all the subjects in order to improve the reliability of the measurements (see Fig. 1).

Short commands were used, such as "Ready" to help subjects prepare for performing the test. Recording was also started at this time. With the command "Go", the subjects performed a throw/kick aiming to achieve the highest possible horizontal velocity of the ball (for the purposes of the subjects, the instruction said "....with maximum force, forward").

Before the recording of the ball throw was started, the subject adopted the standing position, sidewise to the camera. The throwing limb was abducted in the shoulder joint to the angle of ca. 90º and flex in the knee joint to the angle of ca. 90º. The forearm was in the neutral position, with the ball in hand. During recording of kicking the ball, the subjects adopted a standing position, sidewise to the camera, with their foot placed next to each other and parallel. The ball rested on the markers prepared previously on the floor. These markers were made at the half of the distance between the feet and, at the distance of half foot from toes. No approach run was used in the tests.

Calibration of the video material was carried out using a square calibration frame with actual side length of 1.02 m.

After completion of the measurement part, the material collected was processed using dedicated software (AAD4P and SkillSpector v.1.3.2) in order to develop complete databases (in individual and group terms) to contain all the variables studied. These variables were used for statistical analysis using STATISTICA software.

RESULTS

Tab. 1 presents values of maximum moments of forces in the muscle groups measured. The results obtained were consistent with the expectations: M_{max} values recorded in men were higher than in women, whereas anti-gravity strength abilities were higher than the abilities recorded for the gravity groups. It should be added that maximum moments of forces in the muscles of the upper limbs in men were on average by 1.7 to 1.8 times higher than in women and 1.5 to 1.6 times higher than it was the case in lower limbs. It should also be noted that higher values of M_{max} were recorded in the muscles of the dominant body side. In this case, the differences were insignificant and ranged from ca. 1 Nm (elbow joint extensors - EX_E) to ca. 6 Nm (elbow flexors FL_E).

TABLE 1. Maximum muscle torque ($\overline{x}\pm SD$) in the group of women (**W**) and men (**M**); **FL_E**, **EX_E**: groups of elbow flexors and extensors, respectively, **FL_K**, **EX_K** groups of knee flexors and extensors, respectively, **D** – dominant body side, **ND** – non-dominant body side

		FL_E [Nm]	EX_E [Nm]	FL_K [Nm]	EX_K [Nm]
W	**D**	49.3±7.52	29.1±4.83	81.8±16.45	123.4±20.05
	ND	45.1±6.52	28.8±4.52	78.7±14.32	120.1±15.64
M	**D**	87.4±9.88	51.7±8.00	123.5±31.42	201.8±36.81
	ND	81.1±10.14	50.9±7.35	119.7±27.24	195.9±46.61

Fig. 2 compares the values of maximum derivative of the force with respect to time (F'_{max}) that characterizes the rate of force development in individual muscle groups. It should be noted that the highest values of the variables were always reported in men. It can be also easily noted that the hierarchy of values of a particular index is similar for both body sides: the highest rate of force development can be observed in the knee extensors (EX_K), whereas this parameter is the lowest in elbow extensors. All the muscles of the dominant body side in women were characterized with higher mobilization rates (the highest value of F'_{max}) compared to the muscles of the non-dominant side: this pattern was observed in men only for the muscles of the upper limb.
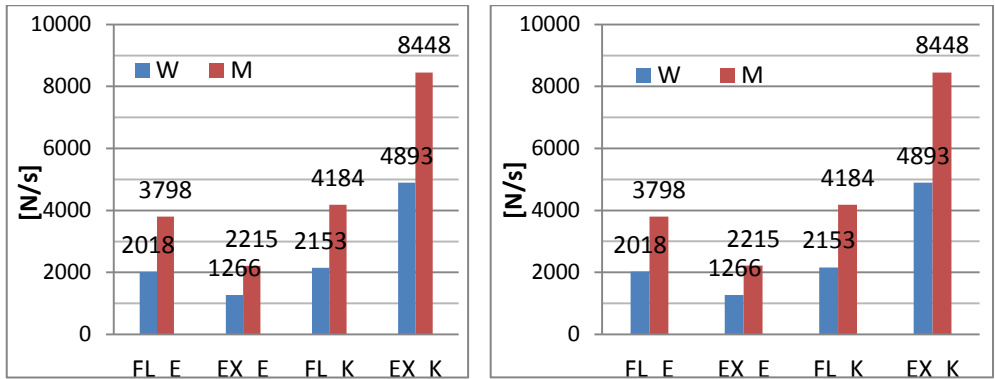

FIGURE 2. Maximum derivative of force with respect to time (F'_{max}) in male (M) and female (W) subjects for fast recruitment of the muscles of the dominant (**left diagram**) and non-dominant (**right diagram**) body side.

Other variables that characterize rate of force development included: time to reach maximum force and time to reach half maximum force (t_{Fmax}, $t_{0.5Fmax}$). With elbow joint muscles, $t_{0.5Fmax}$ was not affected by sex, laterality and muscle function; this index ranged from 0.064 s to 0.078 s. Slightly higher variability was found for

t_{Fmax}, but, similarly, the analysis did not reveal a uniform pattern. The values recorded for limb extensors ranged from 0.269 s to 0.295 s, whereas this range for the antagonists (FL_E) was slightly broader (from 0.256 s to 0.314 s).

Only a slightly more systematized view was obtained for the analysis of time t_{Fmax} and $t_{0.5Fmax}$ with respect to the knee flexors and extensors. Both indices had lower levels (shorter times) in almost every case in the group of men. Furthermore, they were both lower for knee extensors. Time $t_{0.5Fmax}$ ranged from 0.062 s to 0.069 s (knee extensors) and from 0.085 s to 0.188 s (flexors). Analogically, the ranges of variability of t_{Fmax} were 0.232 s to 0.301 s and 0.272 s to 0.375 s, for knee extensors and flexors, respectively.

Fig. 3 illustrates mean values of the horizontal ball velocity in the beginning of the flight phase (v_B). Regardless of the type of motion and gender, the highest values of v_B were recorded for the dominant body side. These differences were more noticeable with respect to throwing: from ca. 3 m/s (women) to ca. 5 m/s (men) compared to kicking the ball (below 1 m/s in both sexes). In the group of women, v_B during throwing ranged from 11 to 14 m/s, whereas in the group of men, this value ranged from 16 to 21 m/s. The speed of the ball kicked with the foot in the group of women was ca. 11 m/s, whereas in men, this was ca. 13 m/s.
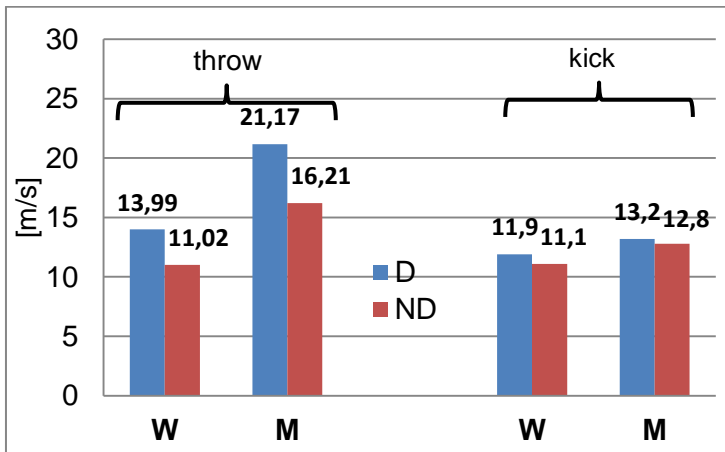

FIGURE 3. Mean horizontal ball velocity (v_B) for the ball thrown or kicked with the dominant (**D**) or non-dominant (**ND**) foot in the groups of women (**W**) and men (**M**).

Tab. 2 presents angular velocities in the knee joint and elbow joint recorded in different phases of ball throwing and kicking. Only the phase of elbow joint extensions was analysed in the first of these movements, whereas the second movement concerned the maximum angular velocity was described both for the phase of knee flexion and extension. This was caused by the limitations of the measurement methodology used. It was found that it was insufficient for causing changes in the angular velocity in the elbow joint flexion during throwing, which

resulted from substantial individual variability of the throwing technique used by the subjects.

Analysis of the Tab. 2 reveals that, during kicking the ball with a foot, the phase of preparatory (knee flexion) is characterized by over twice lower angular velocity than the extension phase. This concerns both sexes and does not depend on laterality. It can be noted that maximum angular velocity (ωK) in the flexion phase was lower than 10 rad/s, whereas in the phase of extension, it exceeded 18 rad/s. It is also remarkable that the angular values recorded for the movement in the knee joint showed insignificantly higher values in men (ca. 1 rad/s).

The maximum angular velocity in the knee joint (ωE) during throwing adopted the values ranging from 27 rad/s to ca. 40 rad/s. Tab. 2 also indicates that ωE recorded in the male group was by ca. 5 rad/s higher than in the female group. Furthermore, when throwing the ball with the dominant hand (D), maximum angular velocity of movement in the elbow joint was ca. 6 rad/s higher than for the non-dominant side (ND).

TABLE 2. Maximum angular velocities ($\overline{x}\pm$SD) in the knee joint (ω**K**) and the elbow joint (ω**E**) for different phases of ball throwing and kicking in the group of women (**W**) and men (**M**); **D** – dominant body side, **ND** – non-dominant body side

		ωK [rad/s]		ωE [rad/s]
		Flexion phase	**Extension phase**	**Extension phase**
W	**D**	8.2±1.97	19.9±3.95	34.7±5.82
	ND	8.4±1.16	18.8±4.15	27.4±5.97
M	**D**	9.3±1.59	21.3±4.05	39.9±6.55
	ND	9.1±2.09	19.7±4.15	33.8±5.82

The above measurement results were subjected to correlation analysis. As expected, all the maximum muscle torques (M_{max}) were correlated, with these correlations being significant. They were stronger for M_{max} in the muscles of a joint (the elbow joint or the knee joint) compared to the relationships between strength abilities in the muscles of the upper and lower limbs. The relationship between M_{max} in elbow flexors and extensors were characterized by the Pearson's r coefficients ranging from 0.75 to 0.92 (women) and from 0.55 to 0.85 (men). Analogically, r values obtained for the muscles of the knee joint in women and men ranged from 0.71 to 0.92 and from 0.58 to 0.94, respectively. As mentioned before, weaker correlations were found between M_{max} in the muscles of the knee joint with M_{max} in the muscles of the elbow joint. These relationships are described by the coefficients of correlations r ranging from 0.54 to 0.64 (women) and from 0.55 to 0.78 (men).

Analysis of the material collected revealed presence of significant relationships between M_{max} with only one index concerning the rate of force development (F'_{max}). Furthermore, higher number of such correlations was found in women, whereas r coefficients adopted higher values compared to men. For the correlation M_{max} vs. F'_{max} with respect to the elbow joint muscles, r value ranged for 0.62 to 0.82 for women and from 0.54 to 0.68 for men. The strength of the same type of relationships (M_{max} vs. F'_{max}) recorded for the muscles of the knee joint in women was demonstrated by the levels of the correlation coefficient between 0.60 and 0.74. A surprising fact in the group of men was the lack of significant correlations for the same type of relationships (although frequently significant values of r coefficient).

Searching for the relationships between strength abilities of the muscles (M_{max}) and rotational velocity in the joints (ωK, ωE) during throwing and kicking the ball did not produce any effects. Both in women and in men, significant correlations could not be found despite the sporadically recorded r values which were close to 0.5.

Significant relationships between M_{max} and the horizontal velocity of the ball (v_B) were observed only in the male group, although the results obtained did not allow for obtaining a coherent picture of these relationships with respect to both types of movements. These correlations were weak and concerned only two cases. The first case was the relationship between maximum strength abilities in the groups of flexors and extensors of the knee joint and horizontal velocity of the ball kicked (v_B) (with r correlation coefficient ranging from 0.53 to 0.54). The second case was the relationship between strength abilities in the muscles of the non-dominant upper limb and velocity of the ball thrown (with r ranging from 0.36 to 0.54).

Analysis of the correlation matrix revealed no significant correlations between the indices that describe the rate of mobilization of the muscles for contraction in women (t_{Fmax}, $t_{0.5Fmax}$, F'_{max}) and angular velocity recorded in the joints during throwing (ωE) and kicking the ball (ωK). No significant correlations were also found between the horizontal velocity of the ball (v_B) and the rate of recruitment of muscle fibres in isometric conditions, both for the muscles of the elbow joints and the knee joints and both for the dominant and non-dominant body sides.

Similarly to women, the male group showed no significant relationships between the rate of mobilization of muscle fibres, angular velocity in the elbow joint and the linear velocity of the ball thrown. Further, the statistical analysis showed significant relationships between selected indices of the rate of force development in lower limbs (t_{Fmax}, $t_{0.5Fmax}$) and the horizontal velocity of the flight of the ball kicked with the foot (v_B). These relationships were characterized by r correlation coefficients ranging from 0.57 to 0.66.

The last element of the correlation analysis was to determine whether there are relationships between the horizontal velocity of the ball flight (v_B) and angular velocity recorded for the elbow and knee joints during movement (ωE, ωK). These correlations in women were not found, whereas positive relationships of this type with medium strength were observed in the male group. Maximum velocity of the ball flight after kicking (v_B) and angular velocity in the knee joint (ωK), were correlated with each other both with respect to the phase of flexion and extension. In the first case, correlation coefficient ranged from 0.43 to 0.47, whereas in the second case, this value ranged from 0.51 to 0.64. The relationship between the speed of the ball thrown and angular velocity in the phase of elbow joint extension did not produce a uniform pattern as the significant relationship was found only for the dominant body side (r=0.59).

DISCUSSION

One of the aims of the present study was kinematic analysis of selected ballistic movements. However, the definition of this type of activity alone causes problems of the fundamental nature i.e. verification whether throwing and kicking the ball can be included under this category. A study by Bober et al. (2007), which compared such activities, demonstrated that their duration is no longer than 0.3 s. In our study, however, the time recorded from starting the movement of the upper limb throwing the ball until the moment of the ball flight was longer. This time was on average 0.37 s in women and 0.42 in men. Similar pattern was observed for ball kicking: the time from the moment of initiation of the preparatory movement until the contact of the foot with the ball was 0.49 s (women) and 0.52 s (men). It should be noted that the values of time contain both preparatory phase (elbow or knee flexion) and the main phase (extension in both joints). The time of ball throwing or kicking might suggest that both motor activities do not belong to movements with ballistic character. However, it can be also noted that these movements depend not only on the concentric activity of the knee or elbow extensors but also on their previous functional elongation during the phase of preparatory (eccentric action). Therefore, if the main action was preceded by a preparatory phase, the question arises whether this swing work should be excluded from the motor activity?

Andersen and Aagaard (2006) might have faced similar dilemmas. They abandoned using time as a factor that determines ballistic movements and included the throws and kicks performed "as fast as possible" i.e. in a manner used in our study.

The main finding of our study was noticeable independence of the motor effect measured (maximum ball speed) in the ballistic movement and static strength abilities (M_{max}) and speed abilities (F'_{max}) of selected muscles in the limbs. Obviously the hypothetical presence of such relationships cannot be excluded.

Analysis of throwing or kicking the ball with the approach run might have produced such correlations. This presumption is based on the data presented in a study by Kellis and Katis (2007), who dealt with the problems of correlations between ball velocity, length and direction of the approach run and functional status of the muscles. These relationships were found, although it should be emphasized that there is a specific threshold of these relationships. It seems that this threshold value can be represented by the ability to perform the movement technically correct, which can be, to some degree, identified with the movement speed. In the present study, the effect of movement technique was attempted to be minimized trough e.g. proper recruitment criteria for selection of the subjects.

Analysis of the literature (Dorge et al. 2002, Kellis and Katis 2007) demonstrates that the level of moment of force developed in individual muscle groups in the lower limbs changes during kicking the ball. These changes occur with changes in joint angles in the hip, knee and ankle joints. Furthermore, just before ball kicking, the direction of the moment of force changes, e.g. in the knee flexors and extensors, which is a manifestation of the mechanism that protects the knee joint from hyperextension (Naito et al. 2010). It is also known that, under conditions of athletic competition, kicking the ball with the foot represents a spatially complex problem. Quality of performance of the kick also depends on the force generated by the groups of abductors and adductors in the hip joint, as they control the motion of the whole lower limb (Nunome et al. 2002). The course of the control represents one of the manifestations of individual technique during kicking the ball, whereas the value of the force in these muscle groups might play the significant role in the motor activity described. The above observations provide a sufficient explanation why the results of laboratory testing of maximum muscle force in the sagittal plane (flexors and extensors of the lower limbs in the joints) are not connected with the effectiveness of kicking the ball (e.g. Shan and Westerhoff 2005). This is also consistent with the results of our study.

The lack of relationships between the indices of strength of lower limb muscles and kinematic variables of the ball kicked suggests similar patterns with respect to ball throwing. Expectation of the independence of motor effects (ball velocity) and functional foundation (maximum muscle strength) resulted from e.g. inclusion of both motor activities into the category of the ballistic activities. This view has been supported by several research studies. Hore et al. (2011) described e.g. changes in the moments of forces in the muscles of the lower limb during various throws, starting from the moment of initiation of the movement of the phase to the beginning of the flight phase. The study suggested that the values recorded for throwing were lower than the maximum values. Unfortunately, no correlation coefficients were calculated for the variables measured. Furthermore, Mirkov et al. (2004) investigated e.g. the relationships between performance of ballistic movements of the upper limb and the explosive muscle force. These researchers

demonstrated that the variables from both groups of factors have weak sporadic (positive) correlations. Among the eight of the presented relationships, only two showed the r correlation coefficient higher than 0.39.

Another argument for the independence of the effect of ballistic movement and maximum strength abilities might be the findings obtained in the study that evaluated the time necessary for reaching the maximum force by a muscle. Ruchlewicz et al. (1996) evaluated the activity of the muscles of the elbow and knee joints under isometric conditions and found that the time necessary for their maximum contraction ranged from 0.18 s to 0.25 s. These values, however, are significantly lower than those postulated by Thorstensson et al. (1976). These authors found that the time necessary for reaching the maximum force exceeds 0.3 s. This value is consistent with the results obtained by Valkeinen et al. (2002) and Singh et al. (2002). The latter team of the researchers dealt with the problems discussed with respect to elite athletes (n=262) from 10 different sports. It turned out that depending on the value of the joint angle and the muscle group as well as specific training, time to reach maximum force might be even twice higher than the discussed threshold (0.3 s). Singh et al. (2002) found this time to range from 0.2 s to over 0.6 s and it should be added that the lowest value was found only for one in twelve measurements. Our study found that the time necessary to reach maximum force by the muscle ranged from 0.23 s to nearly 0.37 s. This means that our results are more consistent to the findings reported by Valkeinen et al. (2002) and Singh et al. (2002) rather than Ruchlewicz et al. (1996). The broad range of variability of the time to reach maximum force by muscles can be explained by a considerable number of factors that affect the results which were presented in detail in a study by Andersen and Aaagaard (2006). The review of the literature shows that the time necessary for achievement of maximum muscle contraction might be longer than the time of the whole ballistic movement.

Referring to electromyographic tests seems to be useful in searching for the relationships between the results obtained for ballistic movements and the functional status of the muscles. Motor effect in a ballistic movement is likely to be more correlated with the process of motor control and nervous and muscular coordination rather than with static strength and speed capabilities of the skeletal muscles. This might be caused by the short duration time for this type of motor activities, which suggests presence of specific automatic patterns for performing these movements. Consequently, the motor effect obtained seems to be based on the accuracy of reproduction of the previously acquired motor program. Undoubtedly, the whole muscle is not excited, which is observed during the tests used for evaluation of maximum strength abilities. This seems to be sufficiently documented by the authors of the above mentioned studies that reported on the lack of significant correlations between strength abilities of muscles and motor effects (Mirkov et al. 2004, Shan and Westerhoff 2005). Performance of a ballistic

movement is likely to excite only the motor units which guarantee its optimal course and, from the standpoint of motor control, this limits the number of these units. The limitation of the excited motor units contributes to reduction of the force generated by the muscles involved. These arguments seem to postulate the inclusion of EMG technique in such tests. It seems that only a comprehensive approach to ballistic movements that considers the state of muscular driving systems, process of muscular control and the course of the motor activity offers opportunities for researchers to minimize problems with interpretation of the results obtained.

Seemingly besides the problems discussed yet in light of the above observations, some doubts can be raised concerning the usefulness of certain motor tests oriented towards determination of the level of human motor abilities. If muscular strength and speed in a ballistic movement is moderate, evaluation of the level of speed or strength based on the results obtained from tests taking less than 0.5 seconds seems to have serious limitations.

Our study found no significant correlations between the speed-related variables (maximal angular velocities in the limb joints ωK and ωE) and the horizontal velocity of the ball (v_B). No correlations were also found between the rate of muscular force development (F'_{max}) in isometric conditions and the above mentioned variables (ωK, ωE and v_B). It seems that these correlations should be expected, because it is easy to imagine the situation that the ball starts moving with the extraordinarily slow preparatory work. In such cases, the ball reaches a very small speed at the beginning of the flight phase. Increasing of the limb velocity during the preparatory phase is aimed at increasing the initial ball flight velocity. However, this reasoning seems to have some limitations, such as time of the motion. With throwing or kicking the ball in a manner that meets the criteria of ballistic movements (short duration time, performing the movement as fast as possible), the relationship discussed is becoming much less clearer. The speed of movement will depend on the speed abilities of the muscles more than on the effectiveness of its use.

Maximum value of vertical ball velocity (v_B) for throwing in the group of women ranged from 11 to 14 m/s, whereas this value ranged in men from 16 to 21 m/s. The velocities when kicking the ball with the foot ranged from 11.1 to 11.9 m/s and from 12.8 to 13.2 m/s for the groups of women and men, respectively. The values of v_B obtained in our study could be compared to the literature reports. However, due to the effect of several factors on this variable (type of approach run or lack of an approach run, mass and size of the ball, technique of performance or e.g. specific sport training or age), such comparisons seem to be illegitimate. Analysis of the values of the velocity of the ball thrown or kicked with the foot published in studies by Barfield et al. (2002), Kellis and Katis (2007), Timmann et al. (2008) supported the above thesis.

Since lower values in the presented ranges of velocity concerned the movement performed with the non-dominant limb, one can see that the direction of the functional asymmetry affects motor performance. Due to its complexity, explanation of the phenomena connected with laterality is beyond the scope of the present study. However, it should be emphasized that the v_B values discussed might be a manifestation of specific adaptations of brain hemispheres to control human body movements. Some studies (Wieczorek and Świerczek 2012) demonstrated that development of these specific adaptations occurs until the age of ca. 12 years. Later, it manifests in functional asymmetry, with two main components being sensory asymmetry and dynamic asymmetry. The latter relates to e.g. quantitative differences in the variables defined for both body sides. The problems of functional asymmetry in the present study were also demonstrated in the strength and speed abilities of the muscles. Analysis of the results reveals the advantage of the muscles of the dominant body side, with all the indices higher for this side, both in the male and female groups.

Values of the variables obtained in our study considered from the standpoint of sexual dimorphism show male dominance with respect to strength and speed abilities (dynamometric examinations) and in motor effect (maximum ball velocity). Various studies on the theory of motor activity (e.g. Osiński 2003) might be useful in the explanation of the reasons for the above levels of indices that characterize the potential aspect of human motor activity. These studies contained the description of some individualities, such as cultural individuality concerning the behaviour in terms of physical activity among the people of both genders. They have also demonstrated that some conditions conducive to motor differentiation are formed since early childhood and, with age, this differentiation is becoming deeper (Staszkiewicz 2013). These conditions are stimulated by higher motor activity and using the muscles of upper and lower limbs (e.g. climbing, throwing, soccer). From the standpoint of these observations, the fact of only sporadic correlations between maximal horizontal ball flight velocity (v_B) and static potential of the muscles in men turned out to be surprising. This supports the above mentioned independence of the effects of ballistic movements from the potential background of the muscles.

CONCLUSION

Analysis of the results obtained in the study leads to the following conclusions:
1. A noticeable independence of the motor effects and static strength and speed abilities of the muscles was observed, despite the fact that only sporadic correlations of this type were recorded in men.
2. No significant correlations were found between the speed variables: maximum rate of force development in static conditions (F'_{max}), maximum rotational velocity in a joint during movement (ωK, ωE) and maximum ball velocity (v_B).

3. The variables that describe the functional status of the muscles and the effects of ballistic movements are determined by sex and functional asymmetry.

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A COMPARISON OF CONVENTIONAL AND NOVEL ANATOMICAL CALIBRATION TECHNIQUES FOR GAIT ANALYSIS

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Abstract: In contemporary gait analysis, motion capture systems are used for accurate, three dimensional tracking of skin markers placed on lower limbs, while related biomechanical model describes lower limb kinematics. Applied procedure introduces errors in calculated gait variables arose from: (1) model calibration errors (2) soft tissue artefacts. Model calibration errors can be eliminated using three dimensional free hand ultrasound technique for anatomical calibration. The purpose of present study was to compare two model calibration techniques: conventional (based on palpation and regression equation) and image-based calibration (based on freehand ultrasound measurement), as well as the assessment of its effect on joint kinematics variables during gait on population of three able-bodied subjects. Results show considerable discrepancy in anatomical landmarks positions (even 44 ±7 mm for hip joint centre) determined using conventional and image-based calibration procedures, resulted in altered kinematic gait characteristics (even 24 ° ± 5 ° difference in hip rotation for selected subject).The study shows that freehand ultrasound imaging technique can be applied as non-invasive, accurate method of anatomical calibration in gait analysis. The further works on implementation of free hand ultrasound imaging technique in gait analysis should concern the development of such calibration procedure, which would provide high precision, that is inter-session as well as inter-examiner repeatability.

Keywords: gait, subject-specific kinematic models, image-based anatomical calibration, freehand ultrasound imaging

INTRODUCTION

Significant research efforts have been made to develop the personalised musculoskeletal modelling technique in recent years [1-2]. Models that included subject-specific details would be even more beneficial for a clinical practise. Detailed anatomical measurements are increasingly used to estimate musculoskeletal loads [3-4] and kinematic description of gait [5].

In contemporary gait analysis, motion capture systems are used for accurate, three dimensional tracking of skin markers placed on lower limbs. On the basis of markers positions and other anatomical measurements, related biomechanical model describes lower limb kinematics [6]. Whilst motion capture systems are sufficiently advanced to not introduce significant errors [7], gait analysis still suffer from a limited accuracy and repeatability [8]. There are two major sources of error: (1) model calibration errors resulting from the difficulty determining the anthropometry of individual subject (2) soft tissue artefacts arising from a skin, muscles and other soft tissue movement in relation to the bones [8]. This paper concerns first source (model calibration errors) which is associated with placing skin markers using palpation method, determining the location of joint centres and definition of joint anatomical axes. Model calibration errors contribute to measurement variability in gait analysis [7-8]. The precision of anatomical calibration affects both joint kinematics and kinetics [7,9].

Potential solution for limitations of contemporary gait analysis is image-based kinematic modelling. Using 3-dimensional imaging techniques to determining anatomical landmarks could eliminate model calibration errors. Application of such techniques to directly determine skeletal movement during walking, which is far more challenging, could eliminate anatomical calibration errors as well as soft tissue artefacts and thereby become a gold reference standard in gait analysis.

The purpose of present study was to compare two model calibration techniques: conventional and image-based calibration, as well as the assessment of its effect on joint kinematics variables during gait. In conventional calibration method anatomical landmarks are located by palpation on the skin surface and position of hip joint centre is estimated using predictive method, whereas in image-based method anatomical landmarks are determined subcutaneously, directly on the bone using non-invasive ultrasonic measuring system [10-11]. Ultrasound calibration was applied to the femur anatomical landmarks during static trial for the standing position. The hip joint and knee joint angles were compared for both calibration methods.

Recent papers evaluate performance of the free-hand ultrasound system[12-13] and bi-planar X-rays imaging technique [14], limited to hip joint centre localization and without consideration of its misplacement effect on joint kinematics. The overall effect of skin marker displacement on joint kinematics was previously theoretically analyzed [7] but not in the context of image-based anatomical calibration. The joint kinematic differences for subject-specific, MRI (magnetic resonance imaging)-based kinematic model and conventional kinematic model were shown in previous work [5], however neither results of calibration procedures comparison nor joint angles patterns were presented.

MATERIAL AND METHOD

Three able-bodied subjects without a walking disability (two female and one male) were analyzed (A: female, height: 167 cm, BMI: 26.89 kg/m2, age: 33 years, B: male, height: 188 cm, BMI: 24.62 kg/m2, age: 25 years, C: female height: 158 cm, BMI: 18.43 kg/m2, age: 26 years). Subjects were on purpose diverse in terms of body mass index.

MODEL CALIBRATION PROCEDURES

All subjects underwent two different anatomical calibration procedures: conventional calibration method and ultrasound image-based calibration procedure.

In conventional calibration method, twelve palpable, external anatomical landmarks of right lower limb (Tab.1), according to ISB recommendation [15], were determined during static trial. Anatomical landmarks defined on skin surface were indicated using navigated pointer (equipped with markers) [16]. Its positions were registered in the reference of corresponding cluster of markers using motion capture system (*Optotrak Certus, NDI, Canada*). The same set of markers was used for gait analysis. Position of hip joint centre was estimated using Davis method [6] and recalculated to femur anatomical coordinate system.

In image-based calibration procedure to measure the anatomical landmarks an ultrasound measuring system has been applied [10-11]. The system consists of ultrasound probe EchoBlaster 128 (*Telemed, Lithuania*) and infrared optical tracking system – *Polaris* (*NDI, Canada*). The applied ultrasound probe is linear, with 80 mm width, and central frequency equals 5 MHz. The recorded scans are squared, 512 x 512 pixels, with 256 shades of gray. Optical tracking system accuracy expressed with RMS value, equals 0.25mm.

The navigation system controls the position and orientation of an active rigid body mounted on ultrasound probe (Fig.1). The ultrasound probe was calibrated to transform the pixel 2D coordinates into the 3D coordinates related to the local coordinate system of a rigid body mounted on probe. The algorithm of coordinate systems transformation enables calculation of probe localization and orientation related to the coordinate system of a particular reference frame (cluster of markers) applied during measurement.

The main advantage of the system is the possibility to measure the spatial geometry of tissues, without specially constructed ultrasound probes typically applied in ultrasound 3-dimensional imaging. Moreover free hand sonography using navigated ultrasound probe has the potential to analyze large objects, unlike the commercial 3-dimensional sonography systems, which are limited to measure a region, or demand performing certain movements of probe over the skin to reconstruct the spatial shape of objects.

TABLE 1. Anatomical landmarks indicated using two anatomical calibration procedures.
* extra anatomical landmarks, which do not define anatomical coordinate system for joint kinematics

	Pelvis	Femur	Tibia	Foot
Conventional calibration method	ASIS R- anterior superior iliac spine right ASIS L- anterior superioriliac spine left midPSIS- midpoint between posterior superioriliac spine	HJC- hip joint centre- Davis equation[6] LE- lateral femoral epicondyle ME- medial femoral epicondyle GT* - greater trochanter	LC- lateral tibial condyle MC- medial tibial condyle LM–lateral malleous MM-medial malleous	Heel* V metatarsal head*
Ultrasound image-based calibration method	-	HJC- hip joint centre- centre of femur head LE- lateral femoral epicondyle ME- medial femoral epicondyle GT* - greater trochanter	-	-

The developed tool provide possibility to define measurement template, where the physicist define on virtual skeleton location of ultrasound scans, virtual markers on virtual scans and geometrical parameters such as lengths, planes or angles. During the real measurement the template is opened and the scans are registered according to the designed scenario.

The system developed by the group of Division of Biomedical Engineering and Experimental Mechanics in cooperation with Clinic of Ulm University and Aesculap BBraun company has already been tested on a group of probands. It has been proven that the correlation between the geometrical parameters measured using this system and based on MRI scans of lower limbs, was very high (0.99). The average differences between these results were about 2.16 mm for lengths measurements and 2° for angle measurements [10].
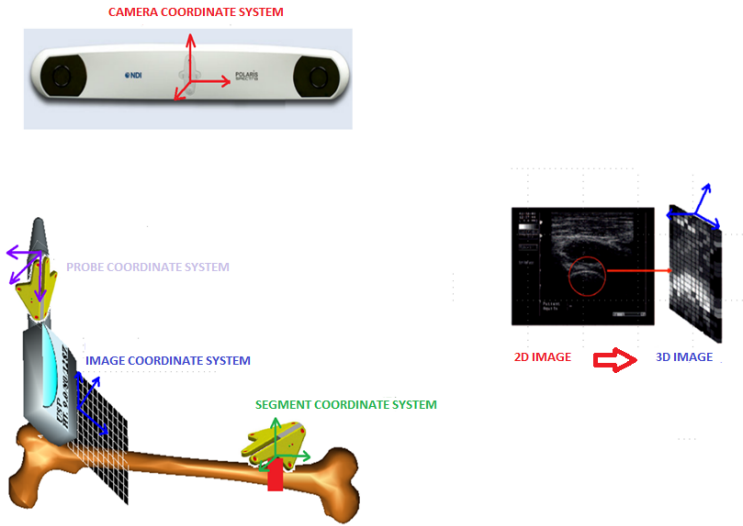
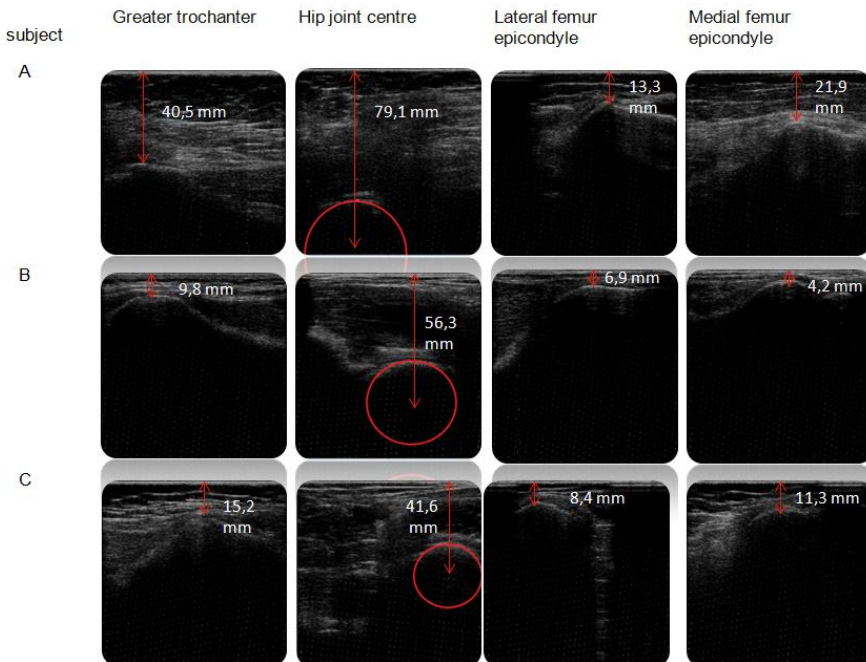**FIGURE 1.** Principle of freehand ultrasound system.

FIGURE 2. Selected ultrasound image of anatomical landmarks with approximate distance from the skin surface.

Four femur anatomical landmarks (greater trochanter, hip joint centre, lateral femur epicondyle, medial femur epicondyle) were scanned using developed system (Fig.2). Six scans of hip joint centre and two for the other anatomical landmarks were recorded. Hip joint centre was determined as the centre of circle matched to femur head contour averaged over four selected scans. The locations of the other anatomical landmarks were determined as position of indicated point on one selected scan.

GAIT ANALYSIS

Marker trajectories were gathered by *Optotrak Certus* motion capture system (*Optotrak Certus, NDI, Canada*) consisted of single position sensor with three embedded cameras. For the data acquisition, joint kinematic calculations, gait visualization and data recording software developed by the author were used [16]. Six-degrees-of freedom gait analysis protocol based on ISB recommendation on definitions of joint coordinate system (6DOF ISB) was used as fully anatomical gait analysis protocol. Thus exclusively anatomical calibration effect on kinematic variables was analyzed without influence of inter-protocol differences.

Four clusters of three non-collinear active markers (*Optotrak Smart Marker Rigid Body, NDI, Canada*) on rigid plates were used to track motion of right lower limb. Clusters were fixed directly on the skin on the pelvis, distal part of thigh, distal part of shank and foot, away from bony landmarks. Such marker configuration enables tracking of each lower limb segment independently allowing 6DOF at each joint (rotational and translational) [17] and 'calibrated anatomical systems technique' (CAST) [18] allows to track any anatomical landmarks on selected segments. Anatomical landmarks are defined as virtual markers, which positions are calculated on the basis of actual clusters position and anatomical calibration data. Anatomical reference frames were defined by anatomical landmarks according to the ISB recommendation [15].

Cardan's angular convention was used to determine the relative orientation of adjacent segments [19]. The three Cardan angles are used to describe the hip and knee joint action of flexion/extension, adduction/abduction, and internal/external rotation.

Subjects walked barefoot with low speed. Three gait cycles for each subjects were selected from the series of recorded cycles. Two different anatomical calibration data sets (conventional and ultrasound-based) were introduced to kinematic model together with measured markers trajectories for each subject. The results are two kinematic descriptions of gait (corresponding to two anatomical calibration methods) for the same set of three gait cycles.

Data was processed, including filtering of marker trajectories with 4th order low-pass Butterworth filter (cut-off 6Hz) and joint angle normalisation to 100 point per cycle. Coordinates of four femur anatomical landmarks (HJC, GT, LE, ME),

indicated by two calibration methods, in reference to femur anatomical coordinate system were recorded. Mean linear distance and distance in each anatomical femur axis (anterior, lateral, superior) between anatomical landmarks determined using conventional and ultrasound-based calibration method, over three subjects were calculated. For visual comparison of two kinematic description of gait, joint angle curves (mean over 3 cycles) were plotted for each subject. Differences between each pair of angles were averaged over gait cycle for each subject and presented in box plots.

RESULTS

There were significant differences between anatomical landmark positions measured with two procedures: conventional and ultrasound- based calibration method, observed in each plane (Tab. 2).Particularly in the case of hip joint centre mean linear difference was substantial (44±7 mm) due to regression equation applied in conventional calibration procedure. Observed differences resulted in altered values and course of kinematic variables (Fig.3, Fig.4).The impact of the anatomical calibration method on kinematic parameters vary across the subjects. Differences between joint angles calculated for two calibration procedure averaged over gait cycle ranges from just a fraction of degree (0.5 ° ± 0.3°, subject C, knee flexion/extension) to tens of degrees (24 ° ± 5 °, subject A, hip rotation). However maximum differences during gait cycle were from 6 °(subject C) to 27° (subject A).

TABLE 2. Linear distance and distance between anatomical landmarks (HJC, GT, LE, ME), indicated by two calibration methods in x anterior, y superior, z lateral in the femur coordinate system

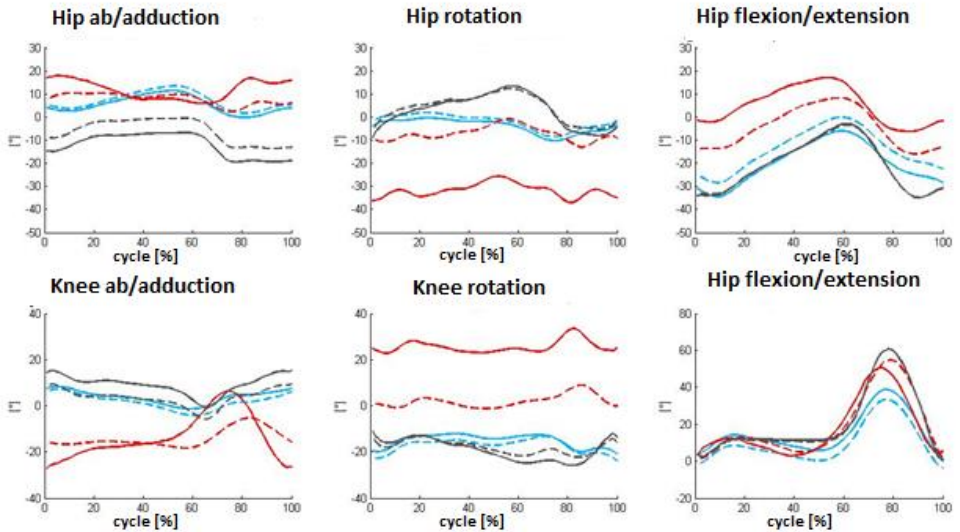|	GT Greater trochanter	HJC Hip joint centre	LE Lateral femur epicondyle	ME Medial femur epicondyle
ΔX [mm] anterior	18 ±10	31 ±13	14 ±4	19 ±7
ΔY [mm] superior	18 ±20	9 ±6	14 ±11	12 ±8
ΔZ [mm] lateral	18 ±23	25 ±12	7 ±5	20 ±7
Δ [mm] linear distance	31 ±24	40 ±7	21 ±8	30 ±9

FIGURE 3. Kinematic variables as calculated for two anatomical calibration procedures: conventional calibration (dashed line) and ultrasound-based calibration procedure (solid line), averaged across three cycles for three subject :A(red), B(blue), C (grey).
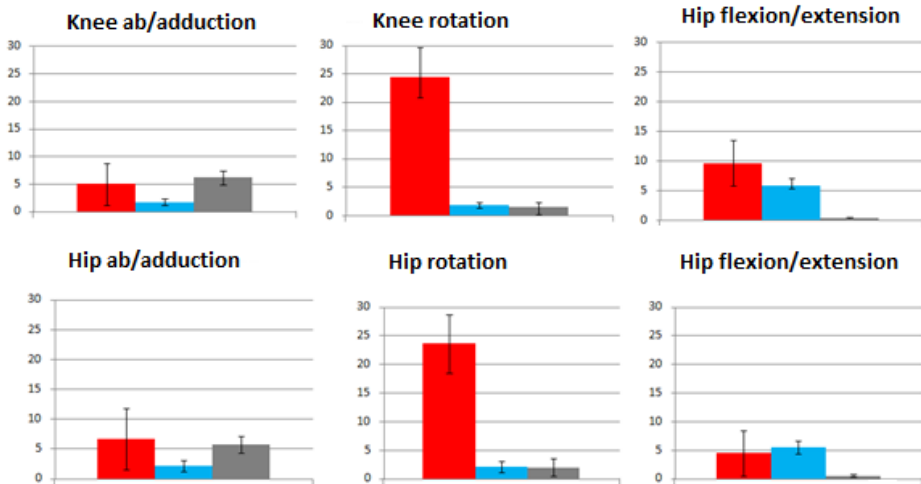

FIGURE 4. Differences between joint angles calculated for two calibration procedure averaged over gait cycle for each subject A(red), B(blue), C (grey).

DISSCUSION

In the study, two different model calibration procedures were applied: conventional calibration method and ultrasound image-based calibration procedure.

In first procedure, navigated pointer was used to indicate palpable anatomical landmarks during static trial before collecting kinematic data. Although markers were not placed directly on palpated points on the skin surface as in case of common calibration, the method is basically the same, but anatomical landmark set differs. Limited repeatability of placing markers results in inter-session and inter-examiner variability of gait parameters [20] and it is one of the principal source of error in gait analysis. Achieving high repeatability is possible, however conventional calibration technique heavily depend on the skill of assessors.

In image-based method the anatomical landmarks are determined subcutaneously, directly on the bone using non-invasive ultrasonic measuring system. Similarly to previous procedure, anatomical landmark positions were measured relatively to reference markers cluster placed on particular segments of lower limb. Anatomical landmarks on ultrasound image presented as bone contours, obviously are rather areas than clearly defined points. Furthermore, interpretation of ultrasound images is difficult, and the bone contour is not always distinguishable from the surrounding tissues. Despite these limitations, the high reproducibility of ultrasound musculoskeletal geometry measurement is possible provided examiner is appropriately experienced [21].

Anatomical landmark positions determined by two calibration methods differ considerably in all planes (Tab.2), which directly results from bone localization under the layer of soft tissue, the choice of point in ultrasound, as well as from position and orientation of ultrasound probe during measurement. Anatomical calibration using ultrasound measurement seems to particularly justified in the case of hip joint centre due to low accuracy of regression equation methods [13].

Obtained discrepancy in anatomical landmark positions affects calculated kinematic variables. Altered values of kinematic variables (in case of each subject) and pattern (especially in case of subject A) were observed. Observed impact of the anatomical calibration method on kinematic parameters vary across the subjects (the higher for subject A ,the lowest for subject C). This could be partially explained by differences in BMI across the subjects followed by discrepancy in AL positions due to thickness of soft tissues, however joint angle differences depends on relative arrangement of two AL sets, which are not directly associated only with thickness of soft tissues. In this study, ultrasound calibration was limited to the femur bone, however greater differences in kinematic variables for both calibration methods could appear if pelvis and tibia anatomical landmarks had been measured using imaging technique.

Obviously accuracy of anatomical calibration can be increased by using imaging techniques, however reliable precision of AL determination, followed by repeatability of gait analysis, still remains a challenge. Currently, there is lack of gait analysis protocol based on ultrasound calibration that would provide high repeatability. The further works on implementation of free hand ultrasound

imaging technique to gait analysis should concern the development of such calibration procedure, which by appropriate measurement protocol together with data processing will provide sufficient precision.

CONCLUSION

The study shows that freehand ultrasound imaging technique can be applied as non-invasive, accurate method of anatomical calibration in gait analysis. Observed considerable discrepancy in anatomical landmarks positions determined using conventional and image-based calibration procedures, resulted in altered kinematic gait characteristics. Use of developed 3-dimensional sonography system allows to eliminate *model calibration* errors, which affect kinematic variables. Moreover, application of free-hand ultrasound technique in gait analysis could increase an inter-session, as well an inter-examiner repeatability if appropriate protocol will be provided.

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