CAN MINIATURE ACCELEROMETERS ATTACHED TO THE GYMNASTICS SPRINGBOARD BE USED FOR TAKE-OFF ANALYSIS?

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Original article

Abstract

An investigation of metric characteristic of a device for measuring vault characteristics during the jump on and take-off from the springboard using a miniature Micro-Electro-Mechanical (MEMS) type accelerometer(s) attached onto the springboard is presented. The measured acceleration is integrated once to obtain the velocity of the springboard during the jump and integrated twice to obtain the springboard displacement. Due to several sources of noise the measured signals were filtered using a Butterworth filter of fourth order with a cut off frequency of 250 Hz and a moving average filter. Several parameters of the jump were extracted from the filtered data such as time to maximal springboard compression, maximal positive and negative velocities and times to achieve these velocities. The obtained parameters are evaluated for their variability and reliability by comparing them to the data obtained by a reference high precision laser sensor measuring springboard displacement. The measurement technique is capable of determining several relevant parameters of the springboard usage with an accuracy of less than 5.3 % for all evaluated parameters except for maximal positive velocity for which an error up to 15.3 % has been obtained. Analysis of 43 jumps of single gymnast proved the reliability of the extracted parameters. MEMS accelerometers can thus be used for analysis of the take-off from the springboard taking into account appropriate filtering of the data is performed before extraction of some parameters that are relevant for the analysis.

Keywords*: metric characteristics, reliability, variability, vault.*

INTRODUCTION

Vault is an artistic gymnastics discipline used by both men and women gymnasts (FIG, 2012a, FIG, 2012b, Dolenec, Čuk, Karacsony, Bricelj, & Čoh, 2006, Ferkolj, 2010). The vault is typically composed of seven phases: runway, jump on the board, take-off from the board, the first flight, support phase, the second flight and the landing (Čuk et al., 2011). During runway the gymnast gains momentum for the vault and with a jump onto the springboard prepares for a change of mostly horizontal linear momentum into a linear horizontal and vertical and rotational (around longitudinal and sagittal axis) momentum. Given that the gymnast cannot significantly change basic parameters of the vault after the take-off, proper gymnast action on the springboard is essential (Dolenec et al., 2006). The gymnast's action on the springboard can be divided into two phases: the first phase in which the gymnast is pressing the springboard from the normal position down to the most compressed position, and the second phase in which the springboard expands back toward its normal position (Čuk & Karacsony, 2004). The time of the gymnast spends on the springboard is short (less than 200 ms) and cannot easily be analyzed in detail by visual observation alone (Atiković & Smajlović, 2011). The most important is the impulse force on the springboard (which is in phase with springboard pressure and displacement) which is defined as product of time and force: $I = Ft = amt = vt^{-1}mt = vm$. As mass is known, the velocity is the main ammount to be evaluated. By determining the proper velocity of the springboard it is possible to analyze springboard behaviour in detail (e.g., time of compression and decompression, length of compression) (Čuk & Karacsony, 2004). According to Ferkolj (2010), one of the most difficult jumps is handspring forward with double salto forward tucked having maximum vertical velocity of about 4.7m/s at the take off. If we presume contact time on springboard of about 200 ms, and if we take 100 ms as the time for take off after maximum springboard compression a 5g accelerometer would be efficient for all women vaults and men vaults up to the handspring double salto forward tuck.

There is a constant need for development of new and/or improved measurement techniques, methods and devices that can improve our understanding and improvement of sport techniques. Several methods and technologies can be used to analyze the vault characteristics. Typically, a video system is used analyze fast movements in slow motion (Sands, Smith, & Piacentini, 2010). High-speed cameras easily achieve speeds of 400 frames/sec which is sufficient to analyze the vault phases in detail (Sands, Smith, & Piacentini, 2010). A drawback of using video is the relatively complicated setup (proper positioning of the camera, light sensitivity, etc.) and a need for complex data processing. On the other hand, an advantage of video systems is the capability of visual evaluation and processing of all phases of the jump not only those depending on the positioning of a particular sensor. Additional information can be gained by using various transducers for displacement, force, velocity, rotation (Marinšek & Slana, 2014) or acceleration. Each of those transducers has some advantages as well as limitations. A force plate is frequently used in biomechanical investigations (Greenwood & Newton, 1996, Pérez et al., 2008, Seeley & Bressel, 2005). Its advantage is well documented usage enabling precise determination of the force pressed to the plate. Some experiments have been performed with electromechanical films; however, the price and complexity of the system preclude more general use of the system (Keränen et al., 2008). In presented investigation, miniature accelerometers were used for evaluation of springboard movement. Nowadays, they are mostly manufactured with Micro-Electro-Mechanical (MEMS) technology making them very small in size and light in weight. Due to the use of semiconductor technology the chips tend to be low cost and therefore suitable for use in mass production devices. Use of miniature accelerometers for movement analysis has been proposed in several studies (James et al., 2004, Kavanagh & Menz, 2008, Pober et al., 2006, Ward et al., 2005, Žagar & Križaj, 2005). One of the disadvantages of accelerometers is that they measure acceleration relative to their position. When an accelerometer is moving together with the object, reliable and precise determination of their position in time presents considerable technical challenges. To reconstruct the correct position of the device it is often necessary to use additional transducers (such as gyroscopes) which measure angular velocity. Some errors in velocity and position determination may occur due to several possible sources of noise. Intrinsic noise is due to the movement of miniature masses inside the accelerometer and incorporated electronics while a discretization error is due to conversion of an analog signal to a digital one. These errors contribute most when the data from measured acceleration are integrated to obtain the velocity and displacement parameters (Žagar & Krizaj, 2005) but can be reduced by usage of suitable accelerometers, proper electronics designs and filtering (Čuk et al., 2011, Preece et al., 2009, Žagar & Krizaj, 2005).

All measurement methods must have appropriate metric characteristics, including validity, reliability, variability and objectivity. Validity checks if the measured characteristics correspond to the actual objective, reliability verifies whether repeated measurements of the same characteristics yield the same results and variability evaluates how different participants can be distinguished from the results of the measurements. Objectivity verifies the measurement results do not depend on the subject (person) performing the measurements (Cozby, 2009).

This report presents an investigation of vault characteristics during the jump and takeoff from the springboard using miniature accelerometer(s) attached onto the springboard. The accelerometer measures acceleration (also gravitational) that is converted to velocity by time integration and measures springboard's displacement through velocity integration. Thereby other important parameters of the jump and takeoff, such as time to reach minimum, maximum and zero vertical springboard velocity, the minimal and maximal springboard velocity and the maximal vertical displacement of the springboard, can be obtained. These metrics are evaluated by comparing the measurements and processed parameters obtained from accelerometers with those obtained from a precision laser displacement sensor.

METHODS

A device (named SkoCi) dedicated for evaluation of springboard movements based on miniature accelerometers was designed and developed (Figure 1). The device is based on a Phillips ARM7 processor which enables low power design and large computational power. It uses ADXL family MEMS type accelerometers from Analog Devices (www.analog.com) which are known to be very reliable and accurate (Kavanagh & Menz, 2008, Žagar & Križaj, 2005). In this investigation a 5g, two axes accelerometer chip ADXL305 was used. The developed device is capable of measuring four signals simultaneously at a frequency of 1000 Hz. In the described experiment two signals were measured: one from the accelerometer for measuring vertical acceleration and one from a reference laser distance meter for measuring the springboard displacement. Measuring the two signals simultaneously with the same device reduced the problems of time synchronization which is often difficult when the signals are measured with different equipment having different sampling rates. Springboard displacement was measured with a laser sensor RF603 from Riftek (www.riftek.com) which uses optical triangulation for precision distance measurements. Laser measurements are due to their reliability often used for evaluation of other measurement devices such as accelerometers (Cheol-Hwan et al., 2012, Gioffre et al, 2000). During measurements the laser sensor pointed directly onto the miniature box containing an accelerometer chip with associated electronics. In our experiments, a sensor with a measurement range of 25 cm and resolution 25 µm or of 0.01% of the measurement range for a digital output was used.

Figure 1. Device (named SkoCi) with an acceleration sensor (visible on Figure 2).

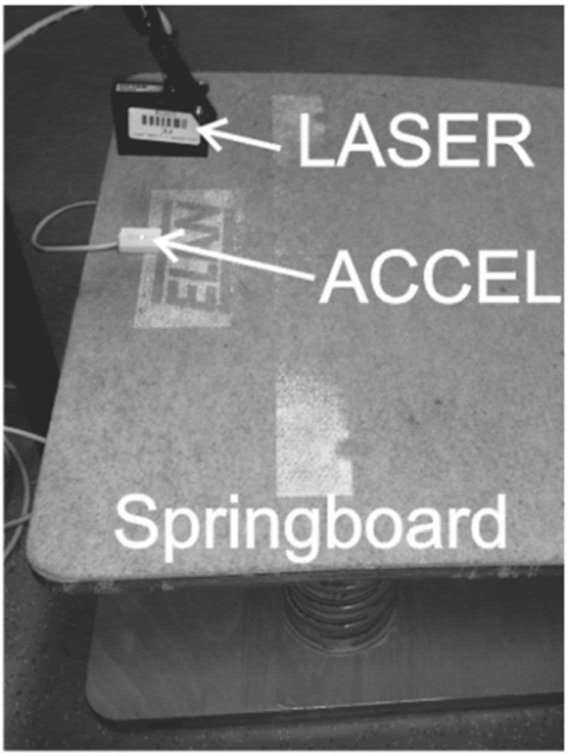


Figure 2. Measurement setup - an optical laser sensor placed directly above the acceleration sensor and pointing a laser beam onto the acceleration sensor.

The measurement setup is presented in Figure 2. The accelerometer chip is assembled on a small PCB plate with some additional elements for proper operation and enclosed in a small box filled and sealed with a two-component epoxy glue. This eliminates any unwanted vibrations of the chip inside the box. Although in practice the acceleration sensor is placed under the top plate of the springboard, in the presented investigation it was placed on top of it (e.g. Figure 2). This enabled exact positioning of the sensor and the laser so that the laser pointed directly onto the middle of the box containing an acceleration sensor, assuring that the accelerometer and the laser measure the same movements and the measurement results can be directly compared. The springboard we used for the experiment is flat from 10 cm before the long wide line and from left to right side to the end. The ideal place for take-off is with feet fingers on the line. As we needed to leave also some space for the take-off of a gymnast the selected accelerometer position shown in Figure 2 was chosen.

43 jumps onto the springboard from one participant (with informed consent; the research was approved by the institutional review board in accordance with Helsinki declaration) were performed in the laboratory conditions. The aim was not to distinguish between different jumps but to identify if the accelerometer can be used to reproduce the lasers's velocity profile of the jump onto the springboard. For this purpose a single participant was sufficient. Participant was 175 cm tall and 83 kg weight. The jumps were designed to be as similar as in the gym pool, with a short runway of 2-3 steps, one leg take-off from the floor, jump onto the springboard and take-off with landing on the floor. Immediately after the jump onto a springboard the SkoCi device (automatically) acquired measured acceleration of the springboard in the vertical direction and simultaneously measured the displacement of the board from the rest position using the laser sensor. The obtained data was gathered from the SkoCi by a personal computer and further processed by Matlab (ver. 7.4; Mathworks, www.mathworks.com). Raw measured data were used for data processing. The acceleration data were scaled and filtered using a Butterworth filter of fourth order and a moving average filter. A cut off frequency of 250 Hz was chosen for the Butterworth filter as it was experimentally determined that it provided the best filtering of the measured signal. An averaging filter is used to eliminate the

so called DC error which is otherwise observed after the integration (needed to obtain the velocity from acceleration) as a linear trend. A window length of one third of the total length of the measured data (per sample) was used for a moving average filter. In order to reduce the phase shift (lag) associated with usage of such a filter a filtfilt Matlab function (filter) was used which enables zero phase filtering by processing the data in both, forward and reverse direction. The data were then numerically integrated to obtain the velocity and once again to obtain the displacement. In a similar way the data from the laser sensor were filtered and then numerically derived to acquire the springboard velocity. During the first phase the top of the springboard moves down accelerating then decelerates toward the maximal bottom position (maximal compression, zero velocity) (Figure 1). After that the springboard goes upward accelerating to a maximal acceleration position and decelerates when the gymnast is off the springboard and continues vibrating after the gymnast's takeoff. Several parameters were extracted from the filtered data. All variables names for laser and accelerometer are same except the first letter, where * is replaced by letter L for laser measurements and letter A for accelerometer measurements: *_t_min_v – time to reach minimum vertical velocity, *_t_0_v_1 –time to maximal vertical negative velocity, *_t_max_v –time to reach maximum velocity, *_t_0_v_2 –time to zero position of the desk, *_min_v – maximum negative velocity, *_max_v – maximum positive velocity, *_max_s – maximum vertical displacement, *_t_max_s – time to maximal desk compression.

Variability, reliability of 2x8=16 variables was analyzed using statistical software package IBM SPSS 22.0. The following tests have been performed: Kolmogorov-Smirnov test, descriptive statistics, koeficient of variation (CV), standard error of measurement (SEM), paired-sample t-test, Pearson correlation, coefficient of determination (R^2) and Cronbach's alpha, and average relative error. Relative error was calculated as absolute difference between laser and accelerometer result and divided with laser result and at the end average relative error was calculated. Bland Altman method of assessing agreement (Bland & Altman, 1986) was calculated with Excel 2010. For calculating Bland Altman figures we subtracted accelerometer values from the values obtained by the laser. All statistics significance for t-test, Pearson correlation and Cronbach's alpha was set to $p<0.05$.

RESULTS

Figure 3 presents a comparison of measured and filtered velocity curves determined from the acceleration measurements using the SkoCi device and laser measurements. Differences were noticed depending on the filtering technique. In general, however, the two sets of results showed good agreement. The parameters obtained from these curves were statistically compared and are presented in Table 1 (Descriptive statistics, Pearson correlation, mean difference, t-test significance). Kolmogor-Smirnov test defined all variables as normal. Coefficients of variation were similar between laser and accelerometer measurements. Standard error of measurements are in general small for both measurement devices, with slightly higher values per specific variables once per laser and once per accelerometer. Person correlations between pairs were significant, high to very high with more than 50% of shared variance. Paired sample t-test significance was observed in most cases; no significant differences in time to reach maximum vertical velocity or maximum trajectory of springboard top, and time to reach minimum velocity, were observed.

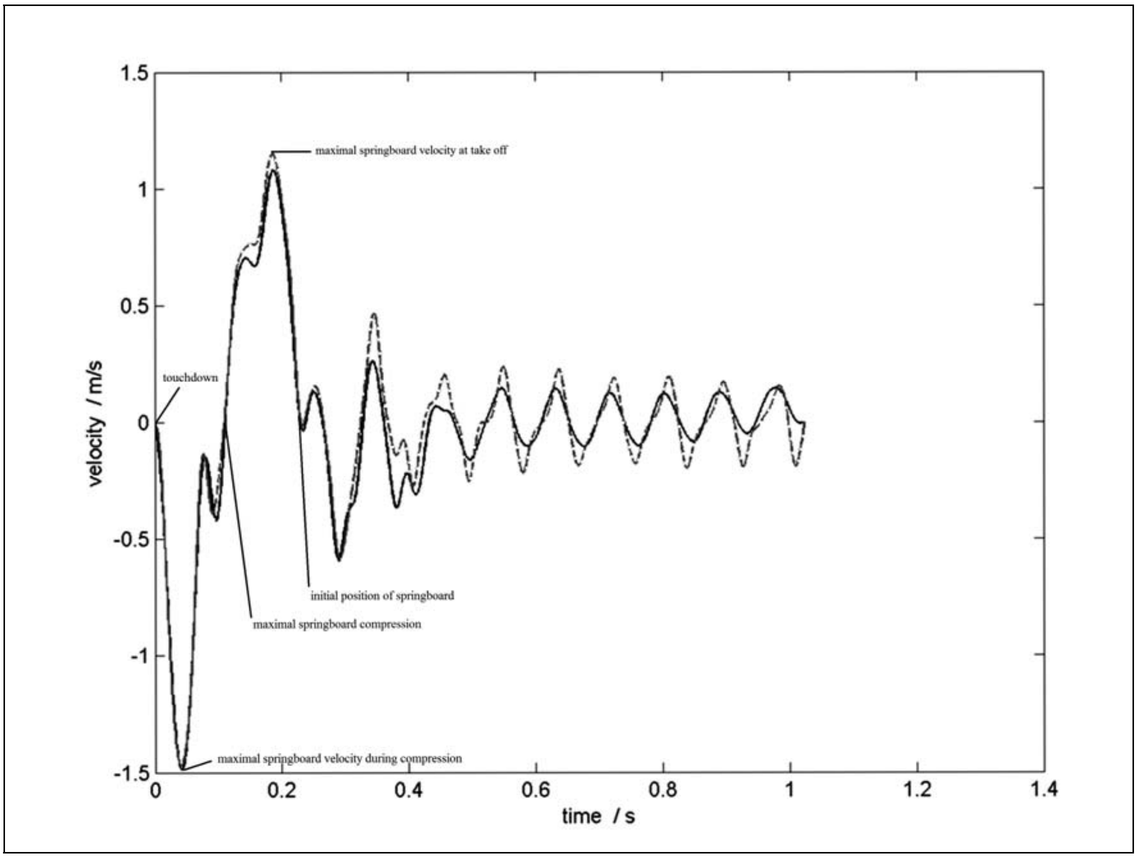
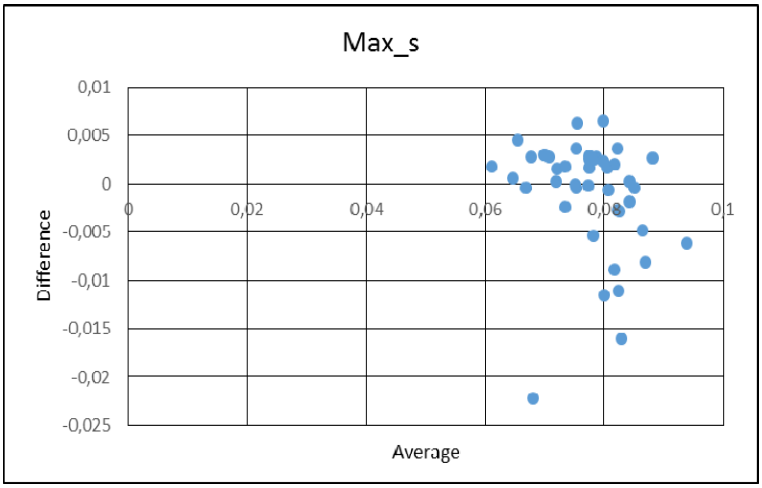
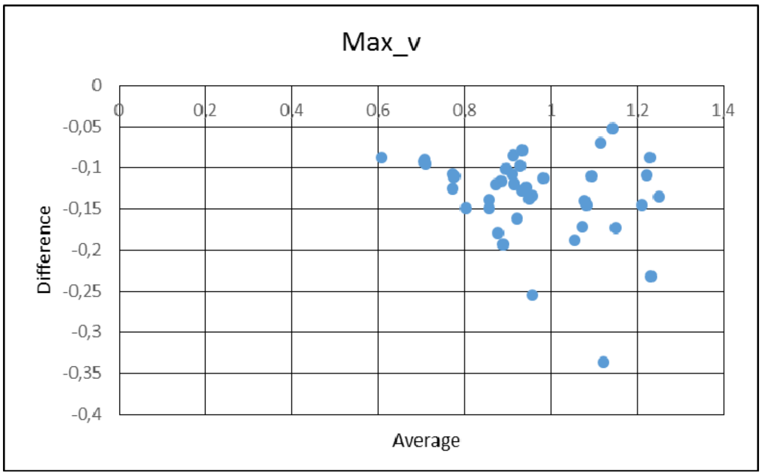


Figure 3. A typical velocity vs. time curve obtained with laser (black line) and accelerometer (grey doted line).

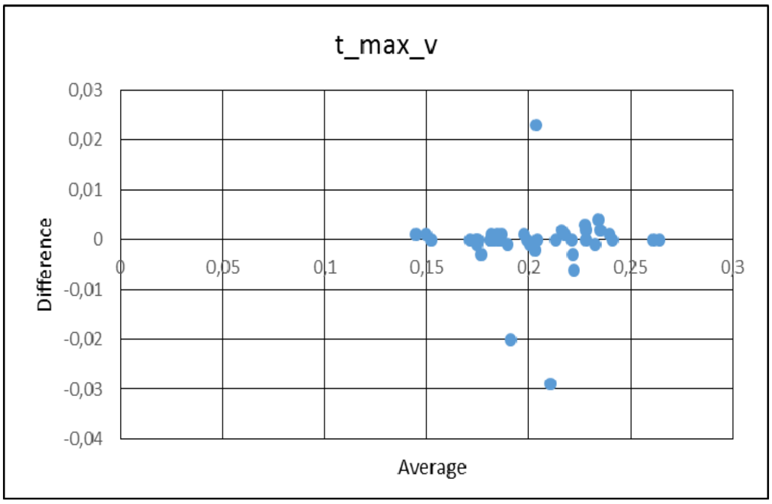
Tables 1 show a large compliance between both measuring devices. A moving average filter which is necessary for balancing the velocity data so that they vibrate around zero velocity has an impact also on the maximal and minimal vertical peak measured by an acceleration sensor. The descriptive statistics shows that the differences between the laser and the SkoCi parameters are small in units. The largest mean difference for time variables is for the time when the springboard gets once more into a normal position and is 0.007 second. Duration of an average take-off in our experiments was 0.258 second for SkoCi which is 3.1% error in comparison with laser results. Time to maximum vertical velocity was 0.201 second and in comparison with average difference from laser this means 0.3% of error. Differences between time variables for laser and SkoCi are small and within the scope of usage in practice. Mean difference in determined minimum velocities for laser and Skoci is 0.05 m/s and is within value of 1.3 m/s which means slightly less than 4% error. Maximum velocity shows more mean difference (0.133 m/s at velocity 1.01 m/s) which results in 13.1% of error for SkoCi (regarding just above mentioned data). For calculating Bland Altman figures (Figure 4) showed high agreement between both methods of measurements.



+1.96 SD=0.012; -1.96 SD = -0.012



+1.96 SD = -0.033; -1.96 SD = -0.239



+1.96 SD = 0.012; -1.96 SD = -0.013

Figure 4. Bland Altman presentation of difference (y axis) and average result (x axis) of maximum length of springboard compression, maximum take off velocity and time from touchdown to maximum velocity.

Table 1.
Descriptive statistics, Standard error of measurement (SEM), Pearson correlation, koeficient of determination (R^2) mean difference, t-test significance, Cronbach's alpha, average relative error.

unit		XA	SD	SE	CV	SEM	Pears. Corr.	R^2	Mean diff.	Sig t-test	Cronbach's alpha	Average relative error
s	L_t_min_v	0,039	0,0157	0,002	40,15	0,004	0,88	0,77	0,002	0,06	0,93	0,049
	A_t_min_v	0,037	0,0139	0,002	37,66	0,014						
s	A_t_0_v_1	0,113	0,0155	0,002	13,71	0,004	0,88	0,78	-0,004	0,00	0,93	0,039
	L_t_0_v_1	0,118	0,0174	0,003	14,74	0,017						
s	L_t_max_v	0,200	0,0284	0,004	14,20	0,003	0,97	0,94	0,000	0,60	0,98	0,012
	A_t_max_v	0,201	0,0283	0,004	14,08	0,028						
s	L_t_0_v_2	0,250	0,0206	0,003	8,24	0,006	0,85	0,73	-0,007	0,00	0,91	0,031
	A_t_0_v_2	0,258	0,0244	0,004	9,45	0,024						
m/s	A_min_v	-1,305	0,337	0,0514	-25,82	0,050	0,97	0,94	-0,053	0,00	0,97	0,046
	L_min_v	-1,252	0,278	0,0424	-22,20	0,278						
m/s	L_max_v	0,886	0,156	0,0237	17,60	0,025	0,95	0,91	-0,133	0,00	0,97	0,153
	A_max_v	1,019	0,169	0,0259	16,58	0,169						
m	A_max_s	0,078	0,008	0,001	10,28	0,003	0,71	0,50	0,000	0,27	0,82	0,053
	L_max_s	0,077	0,007	0,001	9,11	0,007						
s	L_t_max_s	0,116	0,0176	0,003	15,17	0,002	0,98	0,97	0,002	0,00	0,99	0,02
	A_t_max_s	0,114	0,0155	0,002	13,59	0,016						

Letter L for laser measurements and letter A for accelerometer measurements: t_min_v –time to reach minimum vertical velocity, t_0_v_1 –time to maximal vertical negative velocity, t_max_v –time to reach maximum velocity, t_0_v_2 –time to zero position of the desk, min_v –maximum negative velocity, max_v –maximum positive velocity, max_s –maximum vertical displacement, t_max_s – time to maximal desk compression.

DISCUSSION

Calculation of vertical displacement of the top desk of the springboard requires double integration of accelerometer data while for laser we can use raw data directly. The obtained difference was found to be small (less than 1 mm). A series of paired sample t-tests revealed significant differences between laser and SkoCi. However, Pearson correlation coefficients showed in many cases close to linear dependency between laser and SkoCi, what shows high validity of accelerometer. Cronbach's alpha coefficients were all significant and very high showing that rankings are placed correctly and therefore reliability of SkoCi is proper. Reliability calculated with Cronbach' alpha between the laser and the accelerometer compared used technologies. In this case the number of participants was not important. With a single participant we made variance smaller and therefore made a criteria for reliability significance higher. We were searching for such repeatability that is good for each participant itself and also between the participants (with more participants variance would be larger and reliability would improve).

Bland Altman test showed less than 5 % items (1-2) were not within +-1.96 SD difference between laser and accelerometer, what shows good agreement between both methods. While the difference between laser and accelerometer for maximum length of springboard compression and time from touch down to maximum velocity were deviating around 0 points, the difference between laser and accelerometer for maximum velocity showed systematical deviations around a negative average as accelerometer gave higher values of velocity (similar to results of paired sample t-test). In addition, Pearson correlations between differences and averages for all three variables included in Bland Altman test were not significant, which confirms agreement between laser and accelerometer measurements.

CONCLUSIONS

A metric analysis of the parameters measured by a device developed for analysis of springboard parameters in vaulting has been performed. The device is composed of a processing unit and a separate acceleration sensor that is attached below the top desk of the springboard. The accelerometer measures desk acceleration that is collected by the device for further processing. Due to several sources of noise the obtained acceleration data has been filtered by a moving average filter and a Butterworth filter of the fourth order with a cut off frequency of 250 Hz. The filtered data were integrated to obtain the desk velocity and double integrated to obtain the desk displacement. After the jump onto the springboard the desk is first compressed and then released to vibrate after the gymnast's takeoff. In this short time (lasting typically around 200 ms) several indicative parameters can be extracted from data; in particular from the desk velocity profile. Eight parameters were identified and evaluated: time to reach minimum vertical velocity, time to maximal desk compression, time to reach maximal negative and positive velocity, time to zero position of the desk, maximal positive and negative velocity and maximal springboard vertical displacement. Analysis of 43 single gymnast jumps partly proved the validity and reliability of the extracted parameters. The presented investigation has shown that the measurement technique used in a developed device (SkoCi) using miniature MEMS type accelerometers and the filtration technique is capable of determining several relevant parameters of the springboard usage with an accuracy equal of less than (average relative error) 5,3% for all evaluated parameters except for maximal positive velocity for which an average relative error up to 15,3% has been obtained. Despite of high average relative error for velocity for accelerometer, it is important Person correlation and coefficient of determination with laser are very high, therefore relation is almost linear, while amount of differences is high and can be also related to systematic error. A main advantage of the proposed technique is its ease of use and applicability to a wide variety of situations (different types of springboards, training, gymnast skills, etc), however its use in scientific work is questionable.

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FIG. (2012a). Code of Points Men Artistic Gymnastics. Loussane: FIG.

FIG. (2012b). Code of Points Women Artistic Gymnastics. Loussane: FIG.

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