A MULTI-BODY MODEL OF A SPRINGBOARD IN GYMNASTICS

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Case study

Abstract

In order to develop and optimize movements in gymnastics vault, knowledge of take-off velocity and angular momentum is important. Due to the short times of contact on the springboard, high-frequency kinemetric methods are very time-consuming for the determination of the take-off parameters. A multi-body model of a springboard was developed to determine the take-off forces to calculate specific take-off parameters. The Gymnova springboard was modeled using the simulation environment software alaska. The evaluation under dynamic conditions was carried out with a falling mass test, drop-jumps and forward handspring. The evaluation was done on the parameters of the ground reaction forces (GRF): force impact (p) and maximum vertical force (F_{max}). For the drop-jump and forward handspring simulation the real measured acceleration of the upper board was given as input parameter in the model. When comparing the vertical displacement of the real and the modelled upper board, a discrepancy of 6.1 % can be observed. For the falling mass test differences for p=0.4 % and F_{max}=28.2 % were achieved between the real board and the model. For typical loads for the gymnastics sport, drop-jumps have been used. There were realized differences of up to 8.4 % for F_{max} and 6.8 % for p. For the final stage of the review, forward handstand vaults were examined. Horizontal and vertical forces were investigated. Through thorough evaluation on several stages, it was possible to develop a springboard model that is suitable to calculate the GRF under dynamic conditions successfully in 2-d. Therefore, the forces acting on the take-off position can be calculated. Take-off parameters can be determined from these forces. This evaluation also shows that the horizontal forces in especial have to be observed.

Keywords: *artistic gymnastic, springboard, modeling, vault.*

INTRODUCTION

Kinematic methods have been used to determine the specific parameters in gymnastics vault in the past. There the main focus was on the phase of table contact and the phase of flight after table take-off (Chen, Yu, & Cheng, 2009; Dainis, 1979; Yeadon, Jackson, & Hiley, 2014). Due to the short duration of the springboard phase, analyses were highly demanding and therefore difficult to get, so that there were a few individual studies published so far (Sano, Ikegami, Nunome, Apriantono, & Sakurai, 2007). Investigations with 50 Hz video by Farana and colleagues, show that forward vaults of the Kasamatsu (Handspring with 1/4 or 1/2 turn in the flight phase after board take-off) category result in contact times of 0.11 s (±0.02 s) . Due to the short contact time with the athlete on the springboard, a high frequency video was primarily used to calculate take off parameters (Chen et al., 2009; Coventry, Sands, & Smith, 2006). The application of three-dimensional kinematics in conjunction with marker placement or manual digitizing can be very time consuming and therefore inefficient for both, the coaches and the athletes. Furthermore, immediate feedback is missing.

There was a study by Čuk, I., Penic, S., Supej, M., & Križaj, D., (2011) in which the authors have developed a miniature accelerometer to analyse the take-off phase from the board. With this application it was possible to determine the board contact time and the take-off velocity.

In order to determine the acting board forces, a model describing the dynamic characteristics of the springboard will be used. With these forces and properly reduced kinematics, the angular momentum and the take-off velocity can be calculated.

There were already studies that have employed calculation of forces on the springboard. In most cases, the forces under the board were measured and resulting upper board forces were calculated by means of a mathematical model (Čuk, I., Penic, S., Supej, M., & Križaj, D., 2011; Greenwood & Newton, 1996; Sands, Smith, & Piacentini, 2006; Sano et al., 2007). As a result, the authors did not measure the forces that directly affect the athletes on the upper springboard.

For the evaluation of a mathematical model of the springboard, Hao and colleagues chose a static and a dynamic stage (Hao, Wu, Wang, Xiao, & Wan, 2013). In the static stage, the springboard was loaded with known weights and the vertical displacement of the upper board was measured. The displacement of the upper board was used as a comparison for the calculated displacement of the model (Hao et al., 2013). For evaluation of the dynamic properties of the model, they performed drop-jumps and compared the ground reaction forces with a simulated drop-jump in the virtual human modeling and simulation software MSC Adams/LifeMod (Company: LifeModeler, Inc., California, USA).

In all the studies, it was not possible to calculate forces on the upper board which are necessary for the determination of specific take-off parameters (velocity or angular momentum).

The aim of this article was to introduce a model of a springboard and the evaluation of this model under dynamic conditions. First, the development of the model in an iterative process will be shown. Then the dynamic evaluation will be performed by three methods, comparing experimental and simulated data, respectively. In a first step, defined force impacts (equivalent to impulse) were evoked by means of a falling mass test. This falling mass test was based on the standard test procedure for gymnastics equipment of the International Gymnastics Federation. This procedure determines the weight of the falling mass and the drop of height. Furthermore, impact surface, rebound and deflection of the falling mass were defined (Fédération Internationale de Gymnastique, 2006, p. 38). In the second method, test persons performed drop-jumps to realize typical vertical force impacts on the board. Furthermore Motoshima, Kitagawa, and Maeda (2015) had shown in a study that there was a correlation between the Kasamatsu vault and the performance at the drop-jump. Finally, in the last step, a forwards handspring created skill-specific loads.

METHODS

The modeling of the springboard was based on the approach (equation 1) derived by Sano (Sano et al., 2007). This model was built on the following approach: The board

reaction force (BRF) was composed of three main forces, these were:
1) Differences between the effective force below the springboard and ground reaction force (GRF)
2) Less the weight force of the board (m·g) (net weight of the board) and
3) The sum of the forces accelerating the upper boards segments ($m_{Segm} \cdot a_{Segm}$).
$BRF = GRF - m \cdot g - \sum m_{Segm} \cdot a_{Segm}$

The Olympic Gymnova springboard, used in 2012, was modelled using the interactive simulation environment software alaska developed by Institute of Mechatronics, Germany (Institute of Mechatronics, 2014). The model was created based on geometric bodies, technical fixed and revolute joints as well as force elements. The springboard model (Fig 1) consists of an upper board divided into twelve segments. Each segment was linked to its neighbour via revolute joints and torque springs. The typical board curvature was realized by approximated angles at initial conditions. The springs between the lower and upper board were modelled by one-dimensional single force elements. While, the lower frame of the springboard was made of steel and consists of five rigid parts. The board model was coupled to the environment via contact elements with corresponding stiffness parameters (Lehmann et al., 2015; Lehmann, Schleichardt, Naundorf, & Knoll, 2017). The physical input parameters (spring stiffness, modulus of elasticity and rotational stiffness of the torque springs between the segments) were determined experimentally from static experiments.

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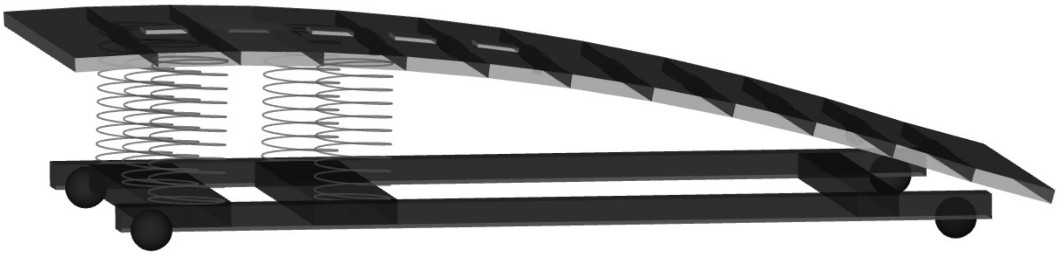

Figure 1. Model of the Gymnova springboard (Lehmann, 2018).

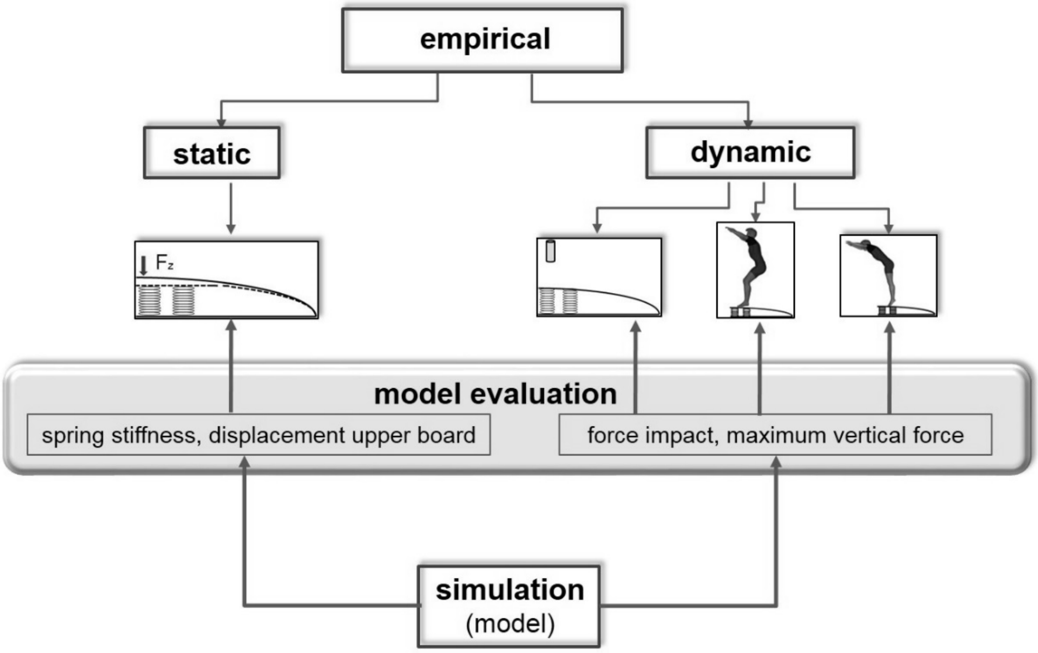

Figure 2. Stages of the model evaluation.

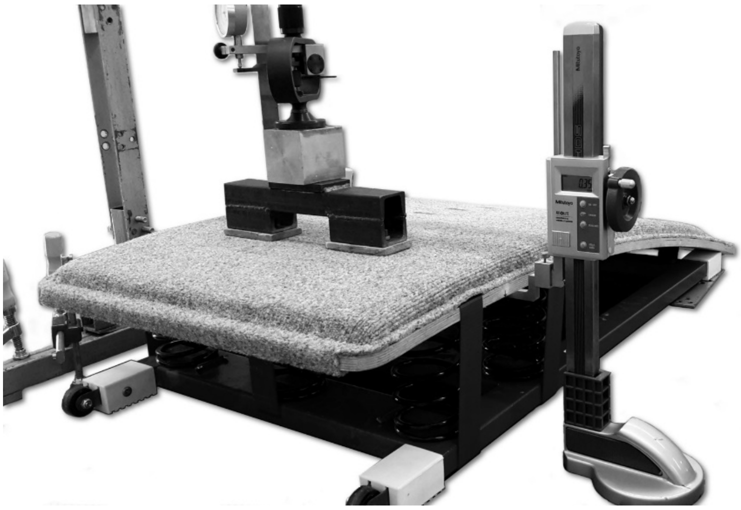

Figure 3. Testsetup for the determination of the vertical displacement (Lehmann et al., 2017).

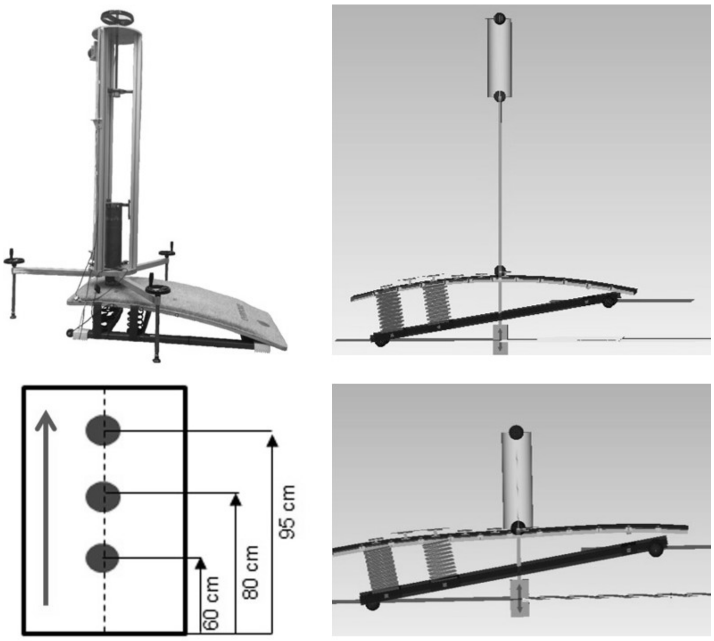

Figure 4. Measuring equipment; Measuring positions with jump direction [arrow] used for standard dynamic test (left), Simulation of the falling mass for MP60 (up: simulation in initial position, down: contact between falling mass and springboard and resulting board deformation, inclined board for vertical impulse generation [MP60: 7.6 °, MP80: 3.1 °]) (Lehmann et al., 2016).

Using the four methods of evaluation (Fig 2), the springboard model parameters were adjusted by method of a standardized static load and typical sport-dynamic loads.

First stage – Static experiments. The static evaluation of the modelled springboard was conducted using the main take-off positions as point of load attack (Coventry et al., 2006). For this purpose, a test apparatus was used which detected the vertical displacement of the upper board of statically transmitted forces. The forces were determined with a calibrated force-measuring device on the upper board. This device consisted of a calibrated mechanical force measuring yoke with dial gauge and a digital height gauge to detect the vertical displacement of the upper board (Fig 3).

With this setup, forces were gradually transferred from 0.4 to 3.6 kN (stepping up, step 0.4 kN) at measuring points (0.6 m, 0.8 m, 0.95 m) measured from the fore edge (Lehmann et al., 2017).

Second stage – Falling mass. For the dynamic comparison between the model and the springboard, it was necessary that defined force impacts were applied to the springboard while the ground reaction forces (GRF) were measured. As it was desired to drop a certain mass vertically from a predefined height, equipment was used according to the guidelines of the International Federation of Gymnastics (Fédération Internationale de Gymnastique, 2006).

For the experimental investigations, three tests were performed (Fig 4) on certain measuring points (MP). The MP were oriented at the main take-off positions (0.6 m [MP60]; 0.8 m [MP80], forward and 0.95 m [MP95], backward vaults). A mass (20.3 kg) was dropped from the height of 0.8 m onto the board. In order to determine the GRF, the springboard was placed on two force plates (0.4 x 0.6 m, 1000 Hz; AMTI Watertown, USA). The springboard was then inclined, depending on the impact point (MP60: 7.6 °, MP80: 3.1 °), in order to make the force impact act perpendicularly to the upper board. Three-dimensional GRF were recorded (1000 Hz). The detected force-time curves were then smoothed for further evaluation with cubic splines. The maximum vertical force ($F_{\max}$) and the force impact (p) were calculated.

For the falling mass simulations, a cylindrical body was added to the springboard model. The falling mass (20.3 kg) dropped from 0.8 m under the affect of gravity onto the model (Fig 4). This ensures that a defined impulse was generated perpendicularly on the springboard. Ground contact elements were used to calculate the vertical GRF.

Third stage – Drop-Jump. For the dynamic evaluation of the model under standardized sport-specific conditions, an athlete (age: 23, mass: 75.4 kg, height: 1.8 m) performed three drop-jumps (DJ) from a gymnastics stool (height: 0.4 m). Ground reaction forces were recorded by means of two force plates (1000 Hz, AMTI Watertown, USA). Three acceleration sensors (he 333 AD 50 g, Hermann Elektronik, Germany) detected the acceleration of the upper board. These were placed in the middle of the upper board (bottom) at the positions MP95, MP80 and MP60.

For the rheonomic condition simulation, the information of the vertical movement of the upper board was calculated from the measured accelerations by two-fold integration over the duration of the contact time. The vertical movement was then applied to the model at locations of MP. The comparison between the model and the real board was carried out for the parameters $F_{\max}$ and p.

Fourth stage – Forward Handspring. A forward handspring was chosen for model evaluation under sport-specific loads. In addition to the vertical GRF, it was of fundamental importance to also calculate the horizontal GRF. A gymnast (age: 23, mass: 75.4 kg, height: 1.8 m) performed at one's own discretion three vaults over a vaulting table (height: 1.35 m). The movement of the upper board on MP80 was measured by acceleration sensors (he 333

AD 50 g, Hermann Elektronik, Germany), the GRF was recorded by two force plates (1000 Hz, AMTI Watertown, USA), as described above. The simulation of the board´s dynamic behavior in forward handsprings was carried out by means of a rheonomic condition. For this purpose, the acceleration signal of the MP80 was converted to a time series of the upper board´s displacement by two-fold integration and made available for the alaska simulation. The simulation started from the first board contact of the athlete to the take-off from the springboard. The horizontal forces were simulated by means of an extra horizontal viscoelastic-damping element between the environment and the springboard frame. Thus, the calculated horizontal forces can be thought of as quasi frictional forces. The mechanical properties of this element were determined by fitting with the experimental data. The comparison between experimental data and simulation data was likewise based on the GRF, i.e., F_{max} and p.

RESULTS

Static experiments. When comparing the vertical displacement of the real and the modelled upper board for the main take-off position for forward vaults, a discrepancy of 6.1 % can be observed (Lehmann et al., 2017). Keep in mind that the model was not set up to reflect static forces. In a practical application, is intended to calculate the forces of the highly dynamic board movement caused by jumps.

Falling mass. With the standardized falling mass test, GRFs were measured. Vertical force maxima F_{max} ranged between 4372 N and 7237 N for each measurement point. Impacts p were determined from 169 Ns up to 171 Ns. The simulated impulse was calculated from 161 Ns to 162 Ns and simulated F_{max} from 4355 N to 5195 N. The resulting relative differences were between 0.4 % and 28.2 %.

Drop-Jump. The evaluations of the vertical GRF of the three experimental drop-jumps (DJ) determined the maximal vertical forces up to 6369 N. The force impulses result from 571 Ns - 574 Ns. The simulated GRF F_{max} were maximal 5677 N. For the simulated vertical impulses p 612 Ns, 612 Ns and 610 Ns were calculated (Table 1). There was high correspondence between the simulated and experimentally determined force-time characteristics of the GRF. This result was also reflected in the percentage calculation of the differences of F_{max} and p. Therefore, for the three DJ the mean differences of 8.4 % for F_{max} and 6.8 % for p between the model and the real springboard have been determined (Table 1). Furthermore, in the simulated deformations, a wave-like deflection was attributed to the highly elastic upper board.

Forward Handspring. For the forward handspring (hs) it appeared that the horizontal forces accounted for to about 40 % of the vertical maximum forces. The vertical and horizontal force-time curves of the three experimental forward handsprings are shown in Fig 5 and Fig 6. The comparison between the simulated and measured vertical GRF yields differences that ranged from 0.7 % to 24.0 %, while for the horizontal forces amounts up to 66.7 % (Table 2).

DISCUSSION

Based on the concept of the mathematical model of Sano (Sano et al., 2007), a multi-body model of the Gymnova springboard was developed in the simulation software alaska. This reflects the dynamic characteristics of the springboard in the 2-d (sagittal plane). Standardized conditions were used to determine the model’s parameters by means of experimental static methods. For this purpose, a comparison of the vertical displacement of the upper board was carried out (Lehmann et al., 2017). For the main take-off position, the smallest deviation (6.1 %) between model and real board could be achieved. Since the model is not intended to only reflect the static conditions, it was evaluated under dynamic conditions at three stages with falling mass tests, drop-jumps and handsprings.

By means of falling mass simulations, the model has been analyzed under standardized conditions for differences in the dynamic behavior compared to the real springboard. In this study, the vertical dynamic feedback (i.e., maximum vertical force together with the impact force) were used for analyzing the differences. A reason for the difference up to 28.6 % in the peak of force in the falling mass tests can be explained by the insufficient interaction between the springs and the dampers of the whole model, including the soft surface layer. Hence, the values of the experiment were achieved almost without deviation, especially at the most compliant measuring point (MP95).

Table 1
Experimental and simulated vertical maximal force (F_{max}) and force impulse (p) and differences for three drop-jumps (dj).

		dj 1	dj 2	dj 3	mean (SD)
experimental	$F_{\max}$ [N]	5962	6369	5680	
	p [Ns]	573	571	574	
simulated	$F_{\max}$ [N]	5297	5677	5309	
	p [Ns]	612	612	610	
difference	$F_{\max}$ [%]	11.2	7.4	6.5	8.4 (2.5)
	p [%]	6.8	7.2	6.5	6.8 (0.4)

Table 2
Experimental and simulated horizontal and vertical maximal force (F_{max}) and force impulse (p) and differences for handspring (hs).

		vertical			horizontal		
		hs 1	hs 2	hs 3	hs 1	hs 2	hs 3
experimental	$F_{\max}$ [N]	7784	7522	8821	2693	3271	2988
	p [Ns]	532	520	522	177	179	164
simulated	$F_{\max}$ [N]	7729	8311	8127	2151	3589	2735
	p [Ns]	515	395	416	59	231	167
difference	$F_{\max}$ [%]	0.7	10.5	7.9	20.1	-9.7	8.5
	p [%]	3.2	24.0	20.3	66.7	-29.1	-1.8

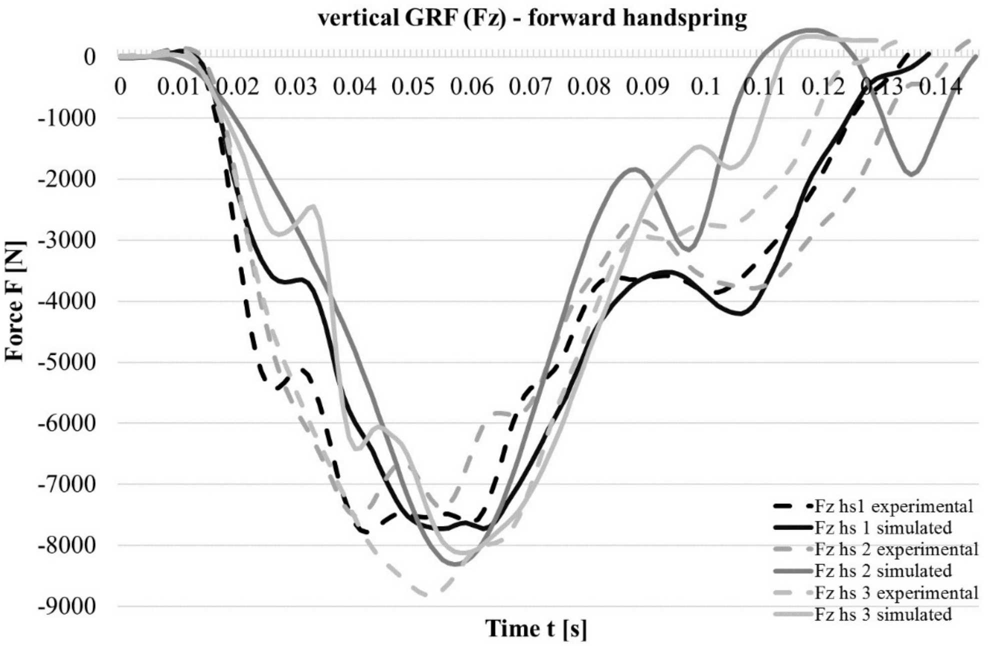

Figure 5. Comparison of simulated and experimentally determined vertical GRF of forward handsprings (hs).

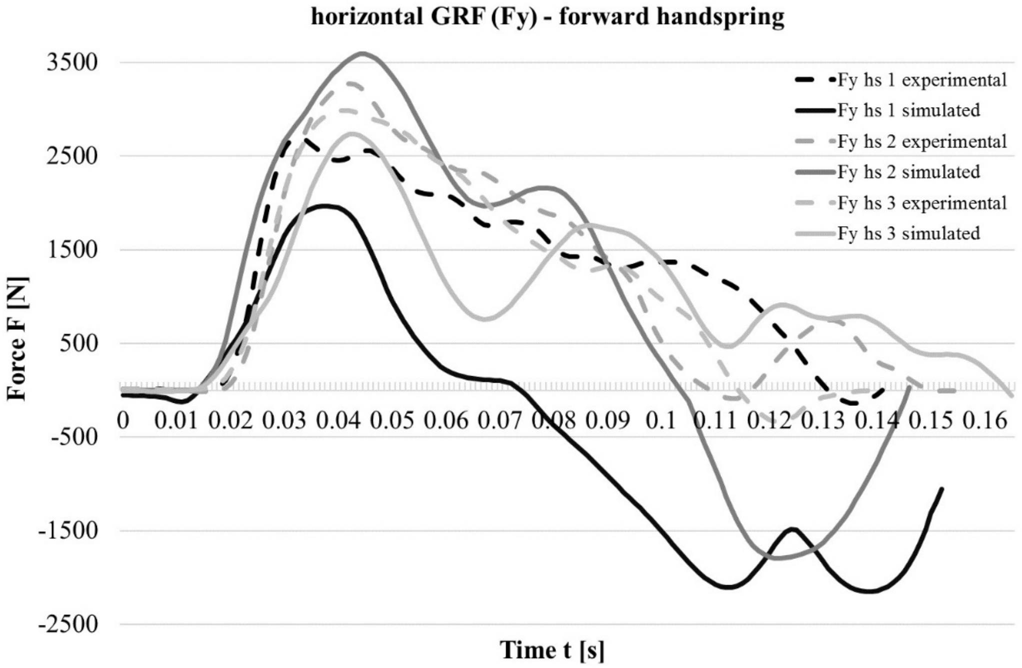

Figure 6. Comparison of simulated and experimentally determined horizontal GRF of forward handsprings (hs).

Sport-specific force impacts were generated in the vertical direction by performing three drop-jumps. For this purpose, the vertical upper-board movement was detected by 3-d acceleration sensors. The recorded data were two-fold integrated during the period of contact between the board and athlete. The calculated board position was transferred to alaska for rheonom condition simulations of drop-jumps. Considering the overall mean percent deviations, differences up to 8.4 % were shown for the vertical dynamic behavior of the board. Hao et al. also used the drop-jump for validation of a mathematic Gymnova springboard model. Hao founded acceptable differences between measured and calculated GRF and disadvantage that high-frequency video-based capturing of the boards movement takes much time (Hao et al., 2013).

The third method of model evaluation was realized by forward handsprings. The upper-board movement was also recorded by acceleration sensors and processed for the rheonomic conditioning of the model. So, the horizontal board movement and forces as well as the vertical GRF could be disclosed. The comparison between the simulated and the measured vertical and horizontal GRF showed differences. Notably, the analysis of the horizontal forces showed differences up to 66.7 %. It can be stated that for the simulation of horizontal "displacement" of the springboard, the application of a viscoelastic element was not appropriate. The force values increased necessarily according to the displacement of the board. Further investigations are required to determine the dynamic behavior (stiffness, damping, friction) between the springboard and the environment in the horizontal direction.

Small deviations (6.1 %) were achieved in the vertical displacement under static load for the main takeoff position (MP60). The resulting impulses for the falling mass tests as well as for the drop-jumps show low deviations in vertical orientation (< 7.2 %). For the handspring vaults these values rose (3.2–24.0 %), in contrast to the peak forces F_{max} showed deviations ranged between 0.7 and 10.5 % for the vertical direction. When comparing the GRF parameters in handsprings, there are still high uncertainties for the calculation of horizontal forces. These large discrepancies could be thought of as a reason for the unacceptable deviations of the vertical impulses for the handspring, as they influence the vertical dynamics indirectly (sum of torques). Further adaptations of the model will be necessary.

In the case of Yurchenko vaults, it should be noted that mainly vertical forces act on the board as in the case of drop-jumps. Due to the satisfactorily agreement of the model to the real board at the drop jump it is conceivable that high agreement of the GRF can also be achieved at Yurchenko vaults.

Another important issue is the quality of the acceleration sensors used to detect board movement. The 50 g acceleration sensors applied in this study seemed to be unsuitable because they didn't give any information about the orientation of the acceleration axes. In the future, inertial measurement units with yaw rate sensors have to be used to detect the initial axis alignment. Thus, it should be possible to generate more accurate input data for displacement control.

Finally the springboard model enables calculation of the forces acting on the athlete. Thus, for this purpose, the upper board movement is detected by acceleration sensors and processed as an input parameter for the simulation. Knowing the center of gravity (COG), entry velocity to the board, the current resulting point of force attack and the calculated vertical and horizontal forces on the upper board, the angular momentum and the take-off velocities of the board can be determined (Wank & Heger, 2009).

There are also some measuring systems (for example Xsens motion capture solution; XSENS, Netherlands) that can be used to provide the COG velocity via sensors and software-based human models. So, it is possible to calculate these take-off parameters in training process much faster than with the conventional kinematic procedures.

CONCLUSIONS

Through thorough evaluation on several stages, it was possible to develop a springboard model that is suitable to calculate the GRF under dynamic conditions successfully in 2-d. This evaluation was realized in four methods: First, in static fashion, to identify spring parameters. Second, with a falling mass in order to load the springboard with defined force impacts under laboratory conditions. The evaluation was done, comparing force-time curves of GRF between the model and the real board. Third, with drop-jumps, the focus was on sport-specific forces. The vertical board displacement was measured using acceleration sensors in order to control the models upper board displacement in simulation. And finally, fourth, with the aid of forwards handsprings, sports-specific loads with a large horizontal portion were generated. In this case, vertical and horizontal GRF were calculated and the parameters p and F_{max} were used as comparative variables, respectively. For the calculation of the vertical peak GRF, deviations of less than 11 % could be achieved. Further model optimization with respect to horizontal displacement and acting friction is necessary to increase accuracy of the horizontal and vertical GRF

In this report the model development and evaluation was presented using the example of the springboard of Gymnova (2012). The evaluation was simplified using drop jumps and handspring performed by one gymnast. The study was designed with an amateur athlete. At the time of the study, no professional athlete was available for laboratory testing. According to the training level of the gymnast and due to the safety of the laboratory conditions handsprings were performed. It was assumed that these simple jumps were sufficient to successfully test the application of the developed method in this pilot study. Since handsprings with following elements and as well as Kasamatsu and Yurchenko vaults will to be investigated in the future, the model must also be investigated and possibly adapted with regard to the transverse forces and force torque. The model will also be extended to the current types of springboards. It is also planned to include other gymnasts (male/female) in the model evaluation.

The method was developed for high-performance gymnastics. Of course, it could also be used in school, amateur sports or physical education. Due to the complexity in the application of the method, it is not recommended for using in non-performance gymnastics.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest whatsoever.

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