MAXIMAL FORCES FOR PEAK HEIGHT AND FLIGHT DISTANCE ON VAULT IN MENS ARTISTIC GYMNASTICS?

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In memory to PD Dr. Klaus Knoll 1941 – 2022
From your gymnastics family.

Abstract

Analysing the take-off forces on the vaulting table can help to inform the athlete about the vaulting technique. A measuring device was used to measure the forces during the Artistic World Championships 2019. The greatest forces were measured during Forward handspring. The mean maximum values were 5.4 times body weight (BW). The highest peak height was calculated for Forward handspring (tucked) at 2.9 m. The longest flight distance was 3.62 m for forward handspring and 3.59 m for tsukahara/kasamatsu. The statistical correlations between the forces and the peak height and flight distance could only be verified for Forward handspring. For the Tsukahara/Kasamatsu and the Yurchenko vaults, no correlation could be proven.

Keywords: men's artistic gymnastics, vault, reaction forces.

INTRODUCTION

The vault exercise is one of the shortest events in Artistic Gymnastics. It involves a 25-meter run-up, jumping on and off the springboard, an explosive take-off from the vaulting table, and a second flight phase with somersaults and twists. Successful execution of the vault is characterized by turns and twists around the body axes, achieving height in the second phase of flight, and a "stuck" landing, as judged by officials.

According to the rules of the International Gymnastics Federation, there must be an evident rise of the gymnast in the second flight phase compared to the take-off from the vaulting table (Fédération Internationale de Gymnastique, 2022).

Numerous research groups have dedicated their efforts to studying this apparatus. Their focus has consistently been on clarifying and explaining the sports technique and its correlation with movement parameters (Prassas et al., 2006). With this knowledge, athletes should aim to execute their technique almost perfectly to receive the highest scores from the judges.

To execute difficult vaults successfully, beginning the vault with the highest possible energy input, manifested as a high run-up

velocity, is essential. Several studies indicate that specific run-up velocities are also necessary for ensuring safe landings for various vaults (Fujihara et al., 2017; Naundorf et al., 2008; Schaerer et al., 2019). The optimal conversion of run-up velocity into vertical and horizontal take-off velocity, along with angular momentum on the vaulting board, has been less explored due to the complex measuring methods associated with the elastic spring system of the board (Čuk et al., 2011). Attempting to delve deeper into this phase, Sano et al. (2007), Lehmann (2018), and Lehmann et al. (2017) modeled take-off forces.

Research on the take-off from the vaulting table has focused on specific vaults or types using kinematic methods. Gutewort et al. (1973) and Leirich (1981) demonstrated that specific body positions can yield corresponding take-off parameters. Studies on the vaulting table for hand-spring forward and double somersault were undertaken by Irwin and Kerwin (2009). Hiley et al. (2015) assessed a planar seven-segment torque-driven computer simulation model of the contact phase in vaulting, specifically for a handspring double somersault vault performed by an elite gymnast. Optimized for both the vault and the athletes, the support phase on the table aims to generate an impulse allowing up to 2.5 rotations about the longitudinal axis and 3.5 rotations about the sagittal axis (Jemni & Sands, 2011).

Ultimately, the athlete's challenge lies in utilizing the energy from the table contact to achieve the required flight time and angular momentum for executing somersaults and twists.

From a mechanical perspective, it can be stated that the vertical take-off velocity (v_z) determines the displacement in height of the center of mass (h_{disp_com}) from take-off to the peak height of the center of mass (h_{peak_com}) relative to the ground.

$$h_{disp\_com} = \frac{v_z^2}{2g} \qquad (1)$$

The take-off velocity (v_z) can be calculated from the integral of the vertical force (F_z) over time.

$$v_z = \frac{1}{m} \int_{t1}^{t2} \dot{F_z} dt + v_{z0} \qquad (2)$$

$$\dot{F_z} = F_z - m \cdot g \qquad (3)$$

"A higher vertical take-off force on the table results in a greater peak BCG height during the second flight, and a higher BCG height after completing both the first and second saltos on the table." (Čuk & Ferkolj, 2008).

It's essential to note that the interaction between the forces on the table and the corresponding position of the body's center of mass (CoM) significantly influences the generation of optimal angular momentum for the second flight phase. The take-off from the vaulting table always involves an optimization between h_{disp_com} and angular momentum. The angular momentum about the lateral axis is consistently reduced during take-off. Additionally, the reduction in angular momentum is less for a handspring forward with stretched somersaults due to the higher angular momentum required for the stretched somersault (greater mass moment of inertia). Conversely, in a handspring forward followed by a tucked somersault, there is a more significant reduction in angular momentum (Knoll, 2002).

It's evident that the take-off from the vaulting table and the reaction forces are crucial. Published studies only cover take-off forces on the vaulting table. Küttner and Knoll (1988) measured forces on the vaulting horse, while during the 2001 World Championships, Schweizer (2003) used the

dynamometric method to investigate forces on the vaulting table, detecting maximum forces of up to 4700 N for the vaults.

Penitente et al. (2011) attempted to measure take-off forces using two portable force plates placed atop the vaulting table. National US Junior Olympic gymnasts participated in this study. Their chosen measurement setup meant the specific elastic properties of the vaulting table did not influence the vault. The study focused on the forces for each hand, recording forces of 1.4 times the body weight (BW; where BW = body mass · g) and vertical force impulses of up to 58 Ns (Penitente et al., 2011).

Knoll and his team employed this measurement method at various events, including the World Cups 2002, German World Championship Qualification 2007, and the German Championships 2008. They recorded forces up to 5 times BW for handspring forward vaults and 2 times BW for Kasamatsu/Tsukahara vaults (Knoll et al., 2014).

The aim of the present study was to determine whether a significant relationship exists between the reaction forces and the peak height of the center of mass (hpeak_com), as well as flight distance, on the vault in gymnastics.

METHODS

During the Artistic Gymnastics World Championships 2019, a force-measuring unit was integrated into the vaulting table, and synchronized 3D videometry was used to record reaction forces and flight parameters. In total, 308 men's vaults were recorded across all four competitions (qualification, all-around final, team final, and apparatus final) at the World Championships. To compare the forces across athletes, they were normalized to their respective body weight (BW). Athletes' body weight was determined using a force system installed on the still rings (Merz et al., 2023).

The force measuring unit utilized a specially developed force plate for the SPIETH vaulting table, equipped with four 3-dimensional (3D) force sensors based on strain gauges, operating at a 500 Hz sample rate. The specifications of the force measuring device and its calibration are detailed in Knoll et al. (2014).

The 3D videometry setup comprised two synchronized full HD cameras (Basler acA 1920–155 uc, USB 3.0, Basler AG, Ahrensburg, Germany; 100 fps; 1920x1200 px), positioned orthogonally in the spectator area. Camera one was situated behind the vault run-up, while camera two was positioned beside the vaulting table. The system's calibration for horizontal and vertical movement directions was achieved by digitizing a 4m measuring stick in both directions.

The dynamometric parameters analyzed included maximum resultant forces ($Fres_{max}$), maximum vertical forces (Fz_{max}), maximum horizontal forces (Fx_{max}), vertical force impulse (pz), as well as kinematic parameters h_{peak_com} and flight distance. These parameters were calculated using specialized software designed for this measurement system (Fig. 1).

Fx_{max} and Fz_{max} are the maximum forces from the captured force-time curves, and p_z is the integral of F_z minus body mass force (m·g) in the limits of the zero-crossing (Fig. 2).
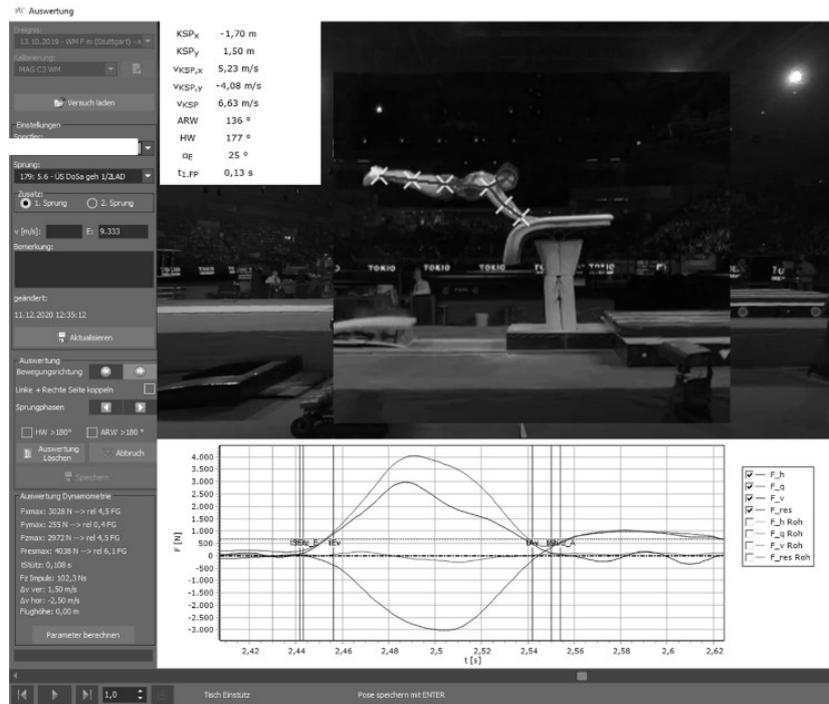
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Fig. 1 Analysis software for the measurement system for vaulting table (MIS VT, measurement and information system vault)
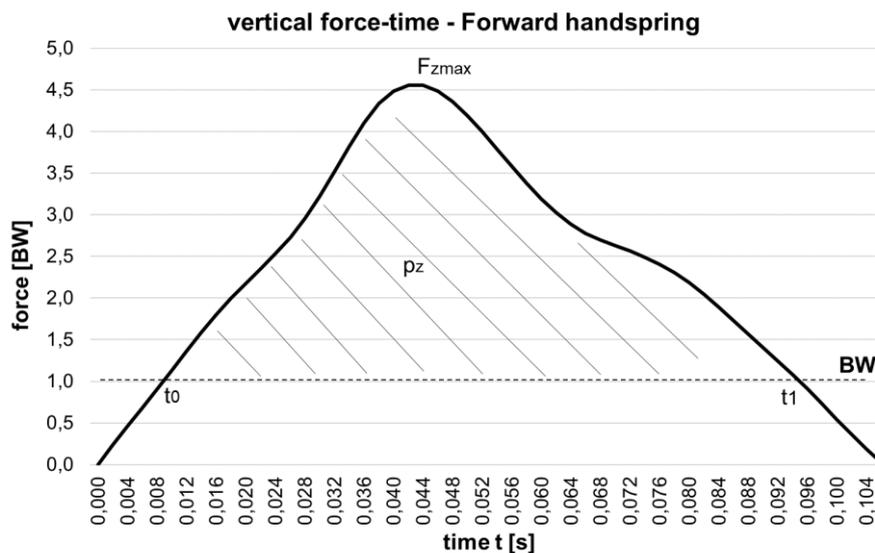

Fig. 2 Example of a vertical force-time curve for a Handspring forward with the evaluated parameters

The h_{peak_com} was determined using the flight parabola (Fig. 3). To establish this, positions at take-off from the table and landing were utilized to determine the trajectory of the CoM. The CoM was determined using a 7-segment model following Zatsiorsky. Thirteen body landmarks (head, 2x shoulder, 2x elbow, 2x wrist, 2x hip, 2x knee, 2x ankle) were manually digitized in a 2D analysis, utilizing

only camera two positioned beside the vaulting table.

The accuracy comparison between 2D and 3D analyses for calculating peak height and flight distance was conducted by Schärer et al. (2019) and confirmed as accurate. Flight distance was defined as the difference between the horizontal take-off position of the hands (average horizontal position of the left and right wrist) and the horizontal position of the feet (average horizontal position of the left and right ankle) at landing.

The evaluation was conducted for vaults categorized into specific vault groups: Forward handspring with stretched somersault and turns, Forward handspring with tucked/piked somersault, Kasamatsu/Tsukahara, and Yurchenko. The subdivision of the Forward handspring was made based on the further reduction of angular momentum during take-off from the vaulting table. The ten vaults with the highest qualitative scores (Execution-Score as determined by official judges) and a difficulty value of >= 4.8 (Fédération Internationale de Gymnastique, 2022) per vaulting group were selected. This resulted in the following distribution of vaults across the vault groups (Table 1) and the E-scores for each vault group (Table 2).
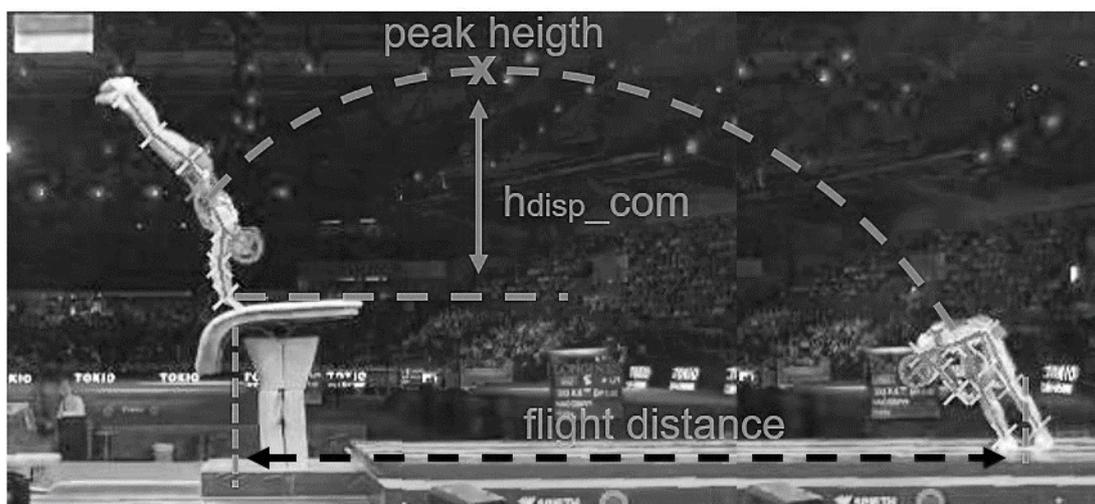

Fig. 3 Calculation of peak height (h_{peak_com}) (related to CoM coordinates) between release from the table and landing distance (hands: take-off from table and ankle at landing)

Table 1
Absolute (N) and relative (%) [of 308 vaults] distribution of vaults in the individual vault groups

vault group	N (WC)	N (D>=4.8)	% (D>=4.8)
Kasamatsu/Tsukahara	196	176	57.1
Yurchenko	41	35	11.4
Forward handspring tucked/piked somersault	50	49	15.9
Forward handspring stretched somersault	23	19	6.2

Table 2
Descriptive statistics of the selected E scores for the vault groups (N=10)

vault group	min	max	mean	sd
Kasamatsu/Tsukahara	9.266	9.466	9.342	.060
Yurchenko	9.200	9.466	9.311	.079
Forward handspring tucked/piked somersault	9.000	9.533	9.229	.178
Forward handspring stretched somersault	8.900	9.300	9.079	.153

All statistical analyses were conducted using SPSS 23 software (SPSS Inc., Chicago, IL). Data normality was assessed using the Shapiro–Wilk test. Descriptive statistics, including median (MD) with interquartile range (IQR) and minimum and maximum values, were computed for each variable across the individual vault groups. Given that the majority of the data did not follow a normal distribution based on the Shapiro–Wilk test and the small sample size, correlations between the reaction forces and flight parameters were evaluated using Spearman's ρ. A significance level of $p < 0.05$ was set. To mitigate the issue of multiple comparisons and reduce Type I errors, the Bonferroni-Holm correction was employed for multiple testing. The classification scheme proposed by Cohen (1988) was used to interpret the effect sizes, where correlations of 0.10–0.29 were considered small, 0.30–0.49 moderate, and $\geq$ 0.50 large.

RESULTS

In the analysis, maximum forces were calculated up to a median (MD) of 5.44 [IQR 4.89-6.38] times body weight (BW) for the Forward handspring tucked somersault vault group. This was followed by the Yurchenko group at 4.64 [3.93-4.88] times BW, Forward handspring stretched somersault at 4.00 [3.07-5.76] times BW, and Tsukahara/Kasamatsu at 3.96 [3.12-4.37] times BW. The highest force components were measured for the Forward handspring (tucked), with maximum horizontal forces at 4.43 [3.89-5.08] times BW and vertical forces up to 3.89 [3.40-3.90] BW. The h_{peak_com} across all vault groups ranged from 2.66 [2.57-2.79] to 2.91 [2.85-2.96] meters. The median flight distance was 3.59 [2.92-4.04] meters for the Tsukahara/Kasamatsu vault group. The greatest vertical impulses were observed for the Forward handspring (tucked) at 93.46 [71.13-102.20] Ns. A horizontal velocity deduction of 2.28 [3.10-2.14] $m·s^{-1}$ was determined for Tsukahara/Kasamatsu vaults (Tab 3).

The following presentation of results is based on the vault groups. The parameter correlations are presented for each vault group. Non-relevant correlations of individual parameters based on their direct mathematical relations (for example h_{peak_com} and h_{disp_com}) were discarded.

Vault group 1a – Forward handspring with tucked/piked somersault

For the vault group performing forward handspring with tucked/piked somersaults, no significant correlation was found between the force parameters ($Fres_{max}$, Fx_{max}, and Fz_{max}) and flight altitude or distance. However, there were significant high correlations observed between $Fres_{max}$ and Fx_{max} (Spearman's $\rho = 0.83$, $p = 0.003$) and between $Fres_{max}$ and Fz_{max} (Spearman's $\rho = 0.83$, $p = 0.002$) (Table 4).

Table 3

Descriptive statistics of the selected sample of vaults per vault group

	Forw. handspring (tucked)		Forw. handspring (stretched)		Tsukahara/ Kasamatsu		Yurchenko	
	MD	IQR	MD	IQR	MD	IQR	MD	IQR
$Fres_{max}$ [BW]	5.44	4.89-6.38	4.00	3.07-5.76	3.96	3.12-4.37	4.64	3.93-4.88
Fx_{max} [BW]	4.43	3,89-5.08	3.15	2.55-4.77	3.41	2.54-4.04	3.53	3.38-4.02
Fz_{max} [BW]	3.89	3.40-3.90	2.56	1.85-3.87	2.87	2.40-3.36	3.09	2.73-3.66
pz [Ns]	93.46	71.13-102.20	48.16	24.27-78.39	41.88	37.38-59.12	81.33	71.69-92.72
h_{peak_com} [m]	2.91	2.85-2.96	2.75	2.53-2.82	2.66	2.57-2.79	2.80	2.74-3.29
h_{disp_com} [m]	0.89	0.82-0.96	0.74	0.53-0.93	0.59	0.53-0.73	0.69	0.64-0.77
flight distance [m]	3.62	3.31-4.12	3.50	3.12-3.80	3.59	2.92-4.04	3.11	3.04-3.29

Table 4

*Correlation and significance for the parameters of the vault group Forward handspring with tucked/piked somersault (*correlation is significant at the 0.05 level)*

	$Fres_{max}$	Fx_{max}	Fz_{max}	h_{peak_com}	flight distance	h_{disp_com}
$Fres_{max}$		0.83*	0.86*	0.36	-0.24	0.71
Fx_{max}			0.65	0.22	-0.30	0.72
Fz_{max}				0.40	0.06	0.41

Vault group 1b – Forward handspring with stretched somersault

In the vault group performing forward handspring with stretched somersaults, $Fres_{max}$ (Spearman's ρ = 0.89, p = 0.000), Fxmax (Spearman's ρ = 0.96, p = 0.000), and Fz_{max} (Spearman's ρ = 0.81*, p = 0.004) exhibited significant high correlations with flight altitude. Moreover, these force parameters ($Fres_{max}$ (Spearman's ρ = 0.90, p = 0.000), Fx_{max} (Spearman's ρ = 0.91, p = 0.000), and Fz_{max} (Spearman's ρ = 0.89*, p = 0.000)) showed significant high correlations with h_{disp_com}. $Fres_{max}$ demonstrated a significant high correlation with both Fx_{max} (Spearman's ρ = 0.95, p = 0.000) and Fz_{max} (Spearman's ρ = 0.92, p = 0.000). Additionally, a significant high correlation was observed between Fx_{max} and Fz_{max} (Spearman's ρ = 0.85, p = 0.020) (Table 5).

Vault group 2 – Tsukahara/Kasamatsu
For this vault group,

There were significant correlations among the force parameters. Specifically, there were notably high correlations between $Fres_{max}$ and Fx_{max} (Spearman's ρ = 0.96, p = 0.000), $Fres_{max}$ and Fz_{max} (Spearman's ρ = 0.90, p = 0.000), and between Fx_{max} and Fz_{max} (Spearman's ρ = 0.88, p = 0.001). Furthermore, a significant high correlation was observed between Fz_{max} and flight distance (Spearman's ρ = 0.72, p = 0.002) (Table 6).

Vault group 3 – Yurchenko
For this group of vaults no significant correlations can be demonstrated (Table 7).

Table 5

Correlation and significance for the parameters of the vault group Forward handspring with stretch somersault (*a correlation becomes significant at the 0.05 level)

	$Fres_{max}$	Fx_{max}	Fz_{max}	h_{peak_com}	flight distance	h_{disp_com}
$Fres_{max}$		0.95*	0.92*	0.89*	0.13	0.90*
Fx_{max}			0.85*	0.96*	0.06	0.91*
Fz_{max}				0.81*	0.05	0.89*

Table 6

Correlation and significance for the parameters of the vault group Tsukahara/Kasamatsu (*a correlation becomes significant at the 0.05 level)

	$Fres_{max}$	Fx_{max}	Fz_{max}	h_{peak_com}	flight distance	h_{disp_com}
$Fres_{max}$		0.96*	0.90*	0.18	0.56	0.31
Fx_{max}			0.88*	0.02	0.52	0.21
Fz_{max}				0.12	0.72	0.30

Table 7

Correlation and significance for the parameters of the vault group Yurchenko (*a correlation becomes significant at the 0.05 level)

	$Fres_{max}$	Fx_{max}	Fz_{max}	h_{peak_com}	flight distance	h_{disp_com}
$Fres_{max}$		0.49	0.62	-0.20	-0.32	-0.37
Fx_{max}			-0.14	-0.49	-0.39	-0.29
Fz_{max}				0.34	-0.08	0.17

DISCUSSION

The results of the presented study show relative forces of up to 5.7 times body weight for $Fres_{max}$ in successful handsprings with stretched somersaults. In the horizontal direction, forces of 4.6 BW were measured during the take-off from the vaulting table for the forward handspring. These findings align with those of Schweizer (2003) and Knoll et al. (2014), who also reported horizontal forces of approximately 3000 N, equivalent to around 5 times BW for the forward handspring. As anticipated, the highest vertical and horizontal forces were measured during the forward handspring with tucked/piked somersaults. Interestingly, the Yurchenko vaults also exhibited resulting forces up to 4.4 BW, with horizontal forces being 3.6 times the body weight and vertical forces at 2.9 BW. It was previously assumed that Yurchenko vaults would generate higher vertical than horizontal forces during take-off from the vaulting table.

Looking at the peak height of com (h_{peak_com}) parameter, the forward handspring with tucked/piked somersault with 2.91 m shows the highest h_{peak_com}. Consequently, this vault group has a substantially higher hpeak_com than the forward handspring with stretch somersault with 2.75 m. This could result from the high push-on effect of the forward handspring with tucked/piked somersault.

With the Tsukahara/Kasamatsu vaults, an average h_{peak_com} of around 2.66 m has been confirmed, as these vaults had a lower take-off angle from the table than those of the other groups. In his investigations, Schaerer et al. (2019) was able to determine h_{peak_com} data of 2.87 m for handspring forward and 2.68 m for Tsukahara/Kasamatsu. Accordingly, the method used in this study appears to achieve similar values.

At the beginning of this investigation, it has been expect that the more forces gymnasts used to take- off the table, the higher and farther gymnasts would fly. This could not be confirmed in the statistical verification.

Instead, the athlete's technique seems to have a decisive influence on the flight height and flight distance.

However, it has to be considered that for forward handspring with tucked/piked somersault and stretched somersault, the horizontal force shows a statistical relationship to the h_{peak_com}.

In further investigations, a comparison of the h_{peak_com} calculated using kinemetry and the flight altitude calculated using dynamometry was also conducted. If a physical relationship can be proven between these methods for the vaulting table, the method of the dynamometry could be used for providing immediate information about the h_{peak_com} and flight distance based on the reaction forces. It is known that there is a physical relationship. However, the accuracy of the calculation methods needs to be verified.

Furthermore, the geometry and physical properties such as damping of the vaulting table should be considered. Given the physical background, these parameters appear to influence influence a) the athletic technique and b) thus, the execution, height, and width of the vault. However, the question posed in the title – whether maximum forces result in maximum peak height and distance - cannot be confirmed. Athletic technique, run-up velocity, and the optimization between reaction force and take-off angle play a decisive role in determining the maximum peak height and flight distance.

CONCLUSION

The study investigated the statistical correlation of the forces during the take-off phase at the vaulting table on the peak height of center of mass and the flight distance. For this purpose, high-level vaults of the World Championship of 2019 have been investigated. The forces were measured at the vault using a specially developed force measuring unit. 2-d kinemetry has been used to evaluate h_{peak_com} and flight distance. The analysis shows a correlation only for the group of forward handsprings. In further investigations, the optimization of angular momentum and h_{peak_com} should also be included in the considerations of the h_{peak_com} and flight distances.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest whatsoever

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