OPTIMAL VELOCITY PROFILES FOR VAULT

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The aim of this study was to determine which kinematic characteristics may be used as a performance indicator(s) for vault. Over 600 vaults (299 men and 216 Women, see Table 1) were recorded and analyzed using footage of 3 high-speed cameras taken at the 2010 Rotterdam Artistic Gymnastics World Championships. The kinematics were correlated with the judge's outcome score: type of vault, difficulty and final score. The correlation coefficients between velocity at takeoff and final judges' scores were r = 0.60 for men and r = 0.52 for women.

KEY WORDS: gymnastics.

INTRODUCTION: Optimal vaulting technique depends on many variables. Analyzing vaults of top athletes performed during World Championships may reveal optimal strategies used by these athletes. The Artistic Gymnastics World Championships 2010 in Rotterdam is halfway through the Olympic cycle and the second last event before the Olympic Games. The field of participating athletes has been narrowed since the first WC in the Olympic cycle but still is broad, 299 men, and 216 women participating. The top athletes may not be at their optimal performance condition during this event because the Olympic Games are still two years in the future. But taking into account the high level of the opponents and relative short gymnastics career performing at their best during the WC is very likely.
The large volume of data (over 600 vaults analyzed) and the quality of the competitors makes this data set valuable in terms of statistical analysis as well as state of the art performances.
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Methods

Over 600 vaults (299 men and 216 Women, see Table 1) were recorded and analyzed using footage of 3 high-speed cameras taken at the 2010 Rotterdam Artistic Gymnastics World Championships. One camera covered the complete runway, one the interaction between gymnast and vault board and one covering the complete vault area form the hurdle step prior to contact on the spring board to landing. All cameras were positioned to acquire a sagittal view, perpendicular to the run-up direction. The sample frequency of the two main cameras was set 100 Hz due to the 'flickering' of the light in the Competition hall. The cameras were calibrated using a standard 2D DLT method.
Software developed at the VU University of Amsterdam in Collaboration with InnoSportNL automatically analyzed all footage and extracted sagittal plane kinematics such as the (optical) center of mass. The data of the run-up camera were then cut just before the landing on the springboard and filtered using a low pass zero phase-lag 4th order Butterworth filter (4 Hz). The flight path of the second flight phase was obtained in a similar way. With information provided by the Fédération Internationale de Gymnastique (FIG) it was possible to relate the kinematics with the Judge's outcome score: type of vault, difficulty and final score.

Run-up

Vaults types were classified as Handspring, Tsukahara, and Yurchenko (Table 1).

Table 1. Number of competition vaults per type of vault and gender.

	Yurchenko	Yurchenko ½	Handspring	Tsukahara	total
Women	168	19	70	21	278
Men	52	4	76	212	346

At the end of the acceleration phase the maximum velocities were 7.7 ±0.3, 8.2 ±0.4 and 8.4 ±0.3 $m.s^{-1}$ and the velocity at takeoff, defined as the last foot contact on the runway, were 6.6 ±0.7, 8.0 ±0.6 and 8.2 ±0.5 $m.s^{-1}$, for Yurchenko, Tsukahara and Handspring, respectively (data for men's competition). All velocities were significantly different between the vault types ($p<0.01$). The maximum velocities for Tsukahara and Handspring (Figure 1) were close to the reported maximum speeds reported for the WC 2007 by Naundorf et al. (2008) who used a laser-based velocity measuring device. The maximum speed of the Yurchenko in this study was greater. The velocity differences could be attributed to the nature of the Yurchenko and definition of the velocity used by Naundorf and the one used here.

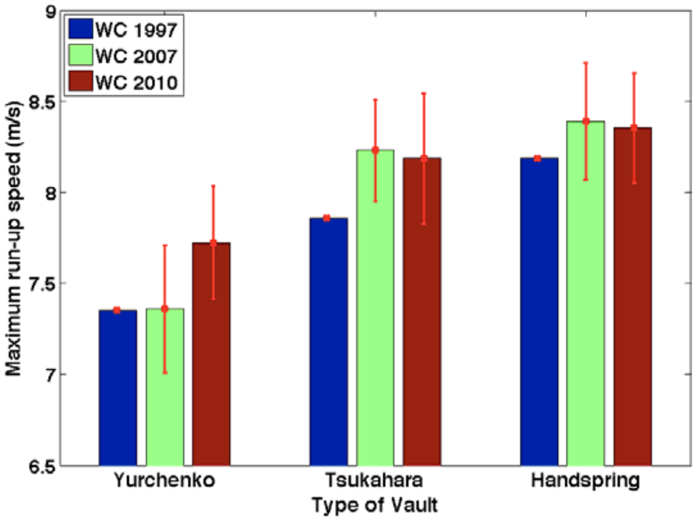

Figure 1: Maximum run-up velocity for 3 different World Championship events. Data for the 1997 and 2007 WC taken from Naundorf 2008.

As Bradshaw et al. (2010) stated the run-up can be divided into a acceleration phase and a 'preparation' or targeting phase when the gymnast adapts speed and stride length for landing on the vault board. The maximum run-up speed is usually achieved few meters before the last foot contact before hitting the board. In almost all Yurchenkos deceleration was very clear with a maximum around -4 m from the last foot contact, where as for the Handspring the deceleration phase occurred between 0 to 1.5 m. The run-up of the Tsukahara seemed to show two strategies, one with a maximum at about 1.5-2 m and one at 0 m, thus no deceleration. These values reported are for men.

Naundorf calculated the run-up speed for a certain type of vault at a predefined distance from the vault table. This method could account for the difference, especially for the Yurchenko, in run-up velocity between their investigation and ours.

Velocity of the run-up has been studied extensively, in training situation (Bradshaw et al., 2010; Brehmer, 2011; Coventry et al., 2006) and in competition (Naundorf et al., 2008; Takei et al., 2000; Sands, 2000; Krug et al., 1998). A few reports investigated the run-up at major events: WC 1997[7], WC 2007 (Krug et al., 1998) and the current report on the WC 2010. The relation between the events is interesting because the WC 1997 dates before the introduction of the vaulting table in 2001 (and other changes). The velocity changes before and after 2001 shows a clear increase in run-up velocity, which can for a large part be attributed to the introduction of the vault table. One of the main reasons for introduction of the Vault Table were safety of the gymnast (Naundorf et al., 2008). Several serious accidents in the past can be attributed to the small landing surface of the old vaulting horse. It is

Interesting to see that the run-up velocity seems to have stabilized between 1997 and 2010. This could indicate that there is a physical limitation to the maximum run-up speed or these are the optimal run-up speeds given the type of vault and setup of the runway and vault table.
Apart from the fact that the run-up speed reached (on average) an optimum, a correlation between takeoff velocity and finale score was found indicating that increased run-up velocity shows an increased final score. The correlation coefficients between velocity at takeoff and final scores were r = 0.60 (0.00) for men and r = 0.52 (0.00) for women.

Flight path in the second flight phase
The horizontal and vertical velocity at takeoff from the vaulting table decides the flight path of the gymnast from takeoff to landing. The average horizontal and vertical takeoff velocities found during the WC 2010 were, 3.20 and 3.18 $m.s^{-1}$ for men and 2.89 and 2.41 $m.s^{-1}$ for women respectively. In Figures 2 and 3 the velocities at takeoff for all vaults are plotted against the final score of the Jury. No relation between horizontal velocity and score was found, whereas there is a clear relation for the vertical velocity: higher vertical takeoff velocity is related to a higher score. The vertical takeoff velocity is directly related to the maximum trajectory height of the center of mass and thus to the time in the air by simple laws of physics, whereas there is no relation between time spend in the air and horizontal velocity. More time in the air gives more opportunity to perform rotations: somersaults and twists. It is therefore clear that for performing more rotations, and thus a higher difficulty (D-score), vertical velocity is of crucial importance and not the horizontal velocity. As an example the vault height is related to the number of twists for a Tsukahara in Figure 4.

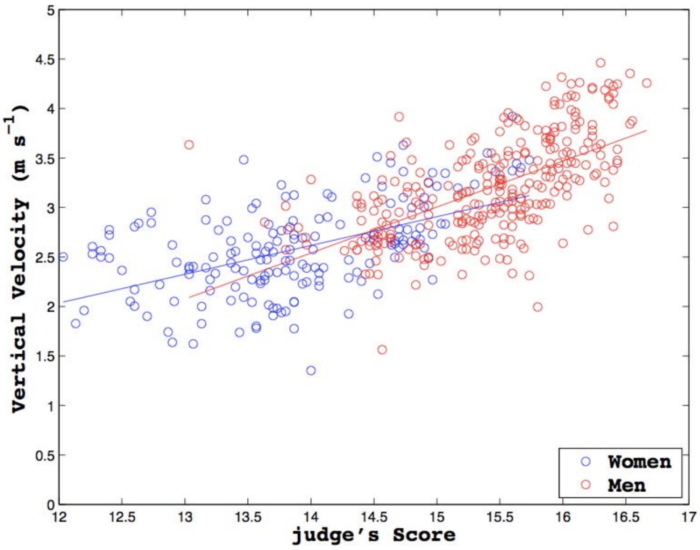

Figure 2: Vertical takeoff velocity from the vault table is plotted against Jury's Final Score for all vaults performed on the WC 2010. Blue are women and red men. A clear relation can be seen: increasing vertical velocity at takeoff is related to a higher final score.

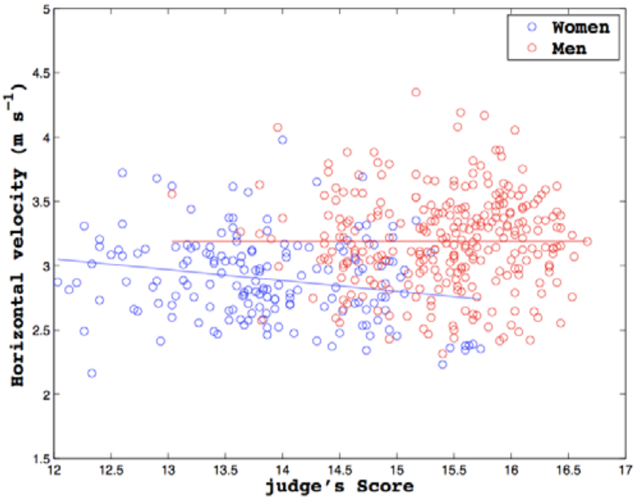

Figure 3: Horizontal takeoff velocity from the vault table is plotted against Jury's Final Score for all vaults performed on the WC 2010. Blue are women and red men. No relation is found.

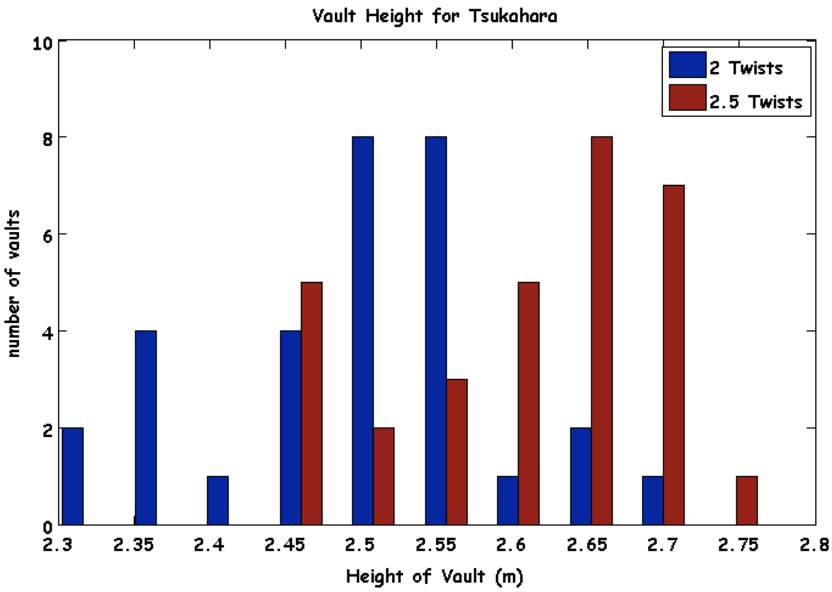

Figure 4: Vault height plotted against the number of twist's of the Tsukahara's performed during the WC 2010 (men). The average vault height for 2.5 twists is approximately 15-20 cm higher.

From these results the optimal flight path can be depicted: it should be high rather then far. Figure 5 shows a typical example of three flight paths all having the same amount of total (linear) kinetic energy. The time in the air increases by ~140 ms going from the shallow blue to the less shallow green and from green to the steep red curve.

As discussed earlier, run-up velocity generates most of the necessary energy. Peak run-up velocity has stabilized over the last years. Given the optimal run-up speed, the effective conversion to vertical speed at the board and table is crucial. This conversion should be optimized in favor of more vertical energy at takeoff from the table. A high horizontal velocity can be a thread to a proper landing. Since the gymnast cannot alter its horizontal velocity in the air, it has to be stopped/absorbed during the landing to make a perfect landing without a forward step. Absorbing the horizontal energy without a step is less difficult with a lower horizontal velocity. The downside could be the increased impact due to the higher flight phase which might pose an extra concern on injuries.

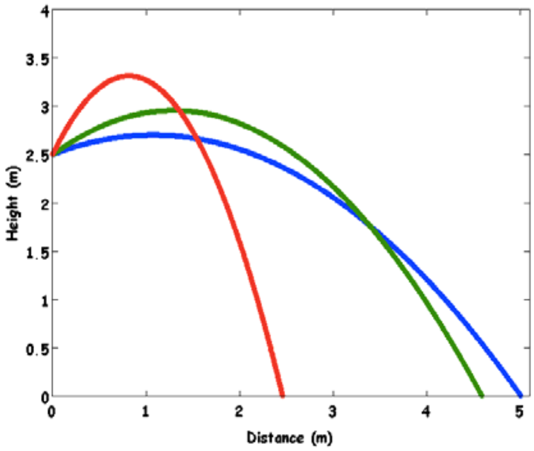

Figure 5: Typical flight paths for 3 different vertical velocities (2, 3 and 4 m.s^{-1}, bleu, green and red resp.). The total amount of (linear) kinetic energy is the same for the three cases. The extra time spend in the air is: 140 and 280 ms for the green and red path.

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