

# **Biomechanical Analysis of the High Jump**

Juha Isolehto, Mikko Virravirta, Heikki Kyröläinen and Paavo V. Komi

Neuromuscular Research Center  
Department of Biology of Physical Activity  
University of Jyväskylä  
Jyväskylä, FINLAND

## **INTRODUCTION**

Richard “Dick” Fosbury won the high jump event at the 1968 Mexico City Olympic Games using a revolutionary new technique named the Fosbury-flop. Two major characteristics of that technique are curved approach run and back layout position. In the present day high jumping, the Fosbury-flop is the sole technique used by all world class high jumpers throughout the world.

The high jump can be divided into three parts: run-up; take-off and flight (or bar clearance). The run-up phase consists of a straight run-up, perpendicular to the plane of the stands, followed by a curved section during the last four to six steps before the take-off. During this phase, the run-up speed of the jumper builds up to between 7 and 8 m/s. The purpose of the run-up is to bring the athlete into an optimum position for take-off, moving at a velocity consistent with the athlete’s strength and skill (Hay 1993).

The take-off phase is defined as a period of time between the instant when the take-off foot first touches the ground and the instant when it loses contact with the ground. The peak height of the centre of mass (COM) during the flight over the bar is dependent on the height and the vertical velocity of the COM at the toe-off instant. This in turn is governed by the jumper’s  $V_v$  at the instant of the touch down and the vertical impulse transmitted via take-off foot to jumper’s body during the take-off phase. The height of the jumper’s COM at instant of toe off depends on his physique and his body position at that instant. (Hay 1973 ).

Dapena et. al. (1990) has found a positive relationship ( $r=0.79$ ) between the horizontal velocity at the end of the run-up and the vertical velocity of the COM during the end of the take-off phase.

Dapena and Chung (1988) presented that fast approach run can help to exert a larger vertical force to the ground. It is interesting to note that the fastest run-ups ever recorded and published in the international meetings were in the World Championships 1997, when the latest biomechanical analysis at the major championships has been done (Brüggemann and Arampatsis 1997).

The present study follows the series of studies collected from the World Championships 1991 and 1997. The purpose of the present study was to determine how the maximum height of the COM during the flight phase is dependent on the kinematic variables of the take-off and update the knowledge about how the development and performance of the Fosbury-flop technique are progressing nowadays.

## **METHODS**

### **Subjects**

Thirteen male high jumpers (height  $192 \pm 0.05$  m, weight  $76.31 \pm 8.13$  kg) were filmed during their competitive performances in the men's high jump final during the 2005 IAAF World Championships. The best valid jumps from each of the finalists were selected for the further analysis. Their mean official record during the final was  $2.27 \pm 0.04$  m. The physical characteristics of the jumpers are presented in Table 1.

## **Data collection**

Two Panasonic (NV-GS400) DV cameras were fixed beyond the perimeter of the track. The distance to the mid-point of the bar was 45 meters and the angle between the optical axes of these cameras was 90 degrees (Figure 1.). The recordings of the jumps were carried out at 50 fields per second with a shutter speed of 1/2000 s. Third camera (JVC GR-DVL 9800) was operating at the speed of 200 fields per second with the shutter speed of 1/250 s and it was positioned perpendicular to the bar (distance from bar was 40 m). Cameras were synchronized using the audio synchronization method (Barros et al. 2006), which records the synchronization signal that was inserted onto the audio track through the camcorder's microphone jack.

Image space was calibrated by using multi phase (5 locations) calibration procedure with the standard calibration frame. Peak Motus software uses a variation of the procedure published in "A Multiphase Calibration Procedure for the Direct Linear Transformation", by John Challis (1995). This procedure was adapted by Peter Vint of Research Integrations Inc.

## **Data reduction**

The digital video signal was captured to the Motus (Peak Performance inc.) motion analysis system. 15 body landmarks (wrist, elbow, shoulder, hip, knee, ankle, tip of the toe on both sides of the body and the head) were digitized manually for the two last strides of the approach and the flight over the bar. The 3D model of the jumper's body consisted of 12 segments. Segment parameters used for determination of the body COM were taken from the data of de Leva, 1996 (adjusted from Zatsiorsky-

Seluyanov's segment inertia parameters 1990). The kinematic data was smoothed by using a Butterworth fourth-order-zero-lag filter and a cut-off frequency of 14 Hz based on residual analysis and qualitative evaluation of the data. Interpolating quintic splines were fitted to the digitized co-ordinate data to allow the estimation of data values at 0.005 s intervals (200 Hz).

### **Coordinate system**

Two different orthogonal co-ordinate systems were used in the present study; XYZ and ABZ (Figure 2.). After the transformation the XYZ co-ordinate system was related to the location of the stands. Origin was the lowest point of the stand nearby the take-off place. The X and Y axes were in the horizontal plane, Y being parallel to the bar and X perpendicular to it. The Z axis was the vertical one. The ABZ co-ordinate system was related to the horizontal direction of the centre of mass during take-off phase. The A and B axes were in the horizontal plane, A being parallel to the final path and B perpendicular to it. The Z axis was vertical.

In the analysis partial heights (H1, H2 and H3) of COM during the take-off phase refer to the height of the jumpers' COM at touch down (TD), toe-off (TO) and peak height, respectively.

## **RESULTS**

### **Partial heights**

The mean values of the partial heights during the TD and TO phases of the take-off were  $0.93 \pm 0.05$  m and  $1.37 \pm 0.05$  m, respectively. The height of the COM at the highest point of the flight was  $2.32 \pm 0.04$  m being  $5.1 \pm 0.33$  cm higher than the

official bar height. These partial height values are often presented as a percentage values compared to the athletes standing height. Table 2. summarizes the results of commonly used partial heights in the high jump.

### **Path of COM prior to and during the take-off and flight**

The curves of the eight best jumpers' paths of COM during the last two strides and the bar clearance are presented in figure. 2. which also shows the different phases separately. The vertical displacement of the acceleration path during the take-off phase was  $0.45 \pm 0.05$  m. The direction of the COM motion during the take-off phase is first downwards, but after  $22 \pm 1$  ms it changes upwards.

The mean take-off angle was  $45.1 \pm 3.5$  °. The angle between the path of the COM during the take-off phase (direction vector, see fig. 2) and bar-line in horizontal plane was  $31.7 \pm 0.2$  °. The highest point of the flight was  $6.34 \pm 0.03$  cm behind the bar-line and the bar clearance place was located  $1.78 \pm 0.08$  m from the stand. The vertical displacement of the COM during flight was  $0.94 \pm 0.07$  m.

### **Horizontal and vertical velocity components**

Figure 3. shows the typical curves of the velocity components of all eight best jumpers during the last two strides, take-off and flight phase. At the TD instant of the take-off the mean horizontal and vertical velocity values were  $7.78 \pm 0.34$  m/s and  $-0.33 \pm 0.15$  m/s, respectively. At the end of the take-off phase (TO) horizontal velocity was decreased to the  $4.31 \pm 0.49$  m/s and vertical velocity was increased up to  $4.30 \pm 0.16$  m/s. Table 3. summarizes the values of the velocity components during the critical phases of the high jump performance.

### **Stride parameters**

The mean contact times were  $147 \pm 16$  ms and  $175 \pm 20$  ms during the 2<sup>nd</sup> last and the take-off contact. The flight time between the last contacts were  $58 \pm 14$  ms. Last stride angle was  $28.5 \pm 4.3$  ° and the length of the last stride was  $2.09 \pm 0.13$  m. The mean perpendicular distance of the take-off contact from the closest stand of the bar was  $1.02 \pm 0.3$  m and  $8.6 \pm 0.4$  cm to the Y direction (see Fig. 2.). Figure 2. shows an overhead view of the footprints and the COM path during the last two contacts of the run-up and in the airborne phase. The exact locations during the different phases for each jumper are also presented. Table 4. summarizes the stride parameters.

During the TD instant of the take-off the mean knee angle was  $168 \pm 14$ °, and it decreased ( $100 \pm 15$  ms) to the  $143 \pm 8.2$ °. At the end of the take-off phase the knee angle was  $174 \pm 3.4$ °. Table 5. summarizes how the knee angles are changing during the take-off phase.

The jumpers' inward and backward inclination values were calculated on the horizontal plane during the take-off contact. This method shows that during the TD phase of the take-off the body has a backward lean of  $36.8 \pm 2.1$ ° but no inward lean at all. Both values are almost zero at the TO instant.

## **DISCUSSION AND SUMMARY**

The mean official results ( $2.27 \pm 0.04$  m) in this competition were one of the poorest during the history of the track and field World Championships since 1983. On the other hand the mean height of the COM during the highest point of the flight was  $2.32 \pm 0.04$  m and that corresponds well to the earlier studies when only six to eight best jumpers were analyzed. From the technical point of view the competition was interesting, because all different kinds of variations of the Fosbury-flop techniques used in this final. These variations are power versus speed –flop and different kinds of hand techniques which are; original running arm action (Topic), leading running arm action (Holm), fast double arm action (Krymarenko) and wide double arm action (Baba).

The results of the approach run demonstrate the fastest run-ups ever recorded. When comparing these values to the earlier studies (Iiboshi et al. 1991; Brüggemann and Arampatzis 1997; Dapena 2000), it seems clear that nowadays horizontal approach velocity is increasing.

The present results show clearly that the vertical velocity and the height of COM at the end of take-off phase together determine the height of the flight ( $r=0.75$ ,  $p<0.01$ ;  $r=0.1$ ., n.s, respectively). Thus, the vertical velocity of the athlete at the end of the take-off phase determines how high the COM will rise after TO. The most important factor related to the vertical velocity of TO is the low COM position at TD ( $r=-0.70$ ,  $p<0.01$ ). These findings are well in agreement with the theoretical findings of Alexander (1990) and the earlier experimental results (Dapena, 1980; Greig and Yeadon, 2000).

The partial heights are very close to the data reported by Iiboshi et. al. (1991) as well as Brüggemann and Arampatzis (1997). These results showed that COM height during the TD is related to hand technique more than physique. Topic, who is using original running arm action, had a lowest value of 68 % of the body height compared to the highest values (73%) of the jumpers who used wide double arm action. This difference in arm actions refers 8 cm, if the jumper is 2m tall. On the other hand, speed floppers like Topic have a shorter take-off time, greater knee angle and higher horizontal velocity during the take-off phase than power floppers. Thus, high knee joint stiffness is crucial for the speed floppers who probably store more elastic energy to the muscle-tendon complex than the power floppers whose take-off is based more on the concentric muscle action. The increased muscle activity of the leg extensors in the braking phase of the contact is also a prerequisite for efficient storage of elastic energy (Komi and Gollhofer, 1997).

It can be concluded that high jumpers with different body types, physical characteristics and performance techniques have good possibilities to compete successfully in the highest level. The different variations of the flop techniques enable the utilization of the best physical capacity of the each individual jumper. Therefore it seems that there is not only one ideal technique to achieve good results.

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Table 1. The physical characteristics of the finalists

Name	height (m)	weight (kg)	BMI	Result (m)
Yuriy Krymarenko	1.85	62.0	18.1	2.32
Victor Moya	1.96	80.0	20.8	2.29
Yaroslav Rybakov	1.96	84.0	21.9	2.29
Mark Boswell	1.89	66.0	18.5	2.29
Jaroslav Baba	1.96	80.0	20.8	2.29
Nicola Ciotti	1.87	75.0	21.4	2.29
Stefan Holm	1.81	70.0	21.4	2.29
Vyacheslav Voronin	1.90	78.0	21.6	2.29
Dracutin Topic	1.97	77.0	19.8	2.25
Kyrikos Iannou	1.93	66.0	17.7	2.25
Oskari Frösen	1.94	86.0	22.9	2.20
Matt Hemingway	1.98	88.0	22.4	2.20
Andriy Sokolovskyy	1.96	80.0	20.8	2.20
average	1.92	76.3	20.6	2.27
standard deviation	0.05	8.1	1.6	0.04

Table 2. The height of the centre of the mass at the instant of touch-down (H1), toe-off (H2) and during the highest point the flight path (H3). The values are also presented as a percentage of the standing height.

Name	H1 (m)	H2 (m)	H3 (m)	Result (m)	H1%	H2%	H3%
Yuriy Krymarenko	0.88	1.32	2.40	2.32	47.51	71.08	2.40
Victor Moya	0.85	1.40	2.38	2.29	43.52	71.22	2.38
Yaroslav Rybakov	0.99	1.43	2.32	2.29	50.56	72.96	2.32
Mark Boswell	0.88	1.36	2.31	2.29	46.46	72.06	2.31
Jaroslav Baba	0.93	1.41	2.33	2.29	47.40	71.79	2.33
Nicola Ciotti	0.86	1.34	2.33	2.29	45.83	71.76	2.33
Stefan Holm	0.87	1.28	2.32	2.29	48.07	70.72	2.32
Vyacheslav Voronin	0.89	1.39	2.30	2.29	46.95	72.89	2.30
Dracutin Topic	0.99	1.34	2.31	2.25	50.30	67.92	2.31
Kyrikos Iannou	0.98	1.36	2.29	2.25	50.67	70.47	2.29
Oskari Frösen	0.97	1.42	2.29	2.20	50.05	73.40	2.29
Matt Hemingway	0.97	1.43	2.32	2.20	49.19	72.37	2.32
Andriy Sokolovskyy	0.97	1.40	2.24	2.20	49.44	71.33	2.24
average	0.93	1.37	2.32	2.27	48.15	71.54	2.32
standard deviation	0.05	0.05	0.04	0.04	2.15	1.41	0.04

Table 3. The vertical ( $V_v$ ) and the horizontal ( $V_h$ ) velocity values at the instant of the touch-down (TD) and the toe-off (TO) phases during the take-off. The projection angle of the COM and the change of the horizontal velocity during the contact ( $\Delta V_h$ ).

Name	$V_h$ TD	$V_h$ TO	$\Delta V_h$	$V_v$ TD	$V_v$ TO	angle
Yuriy Krymarenko	7.99	4.35	3.64	-0.45	4.61	51.68
Victor Moya	7.36	3.75	3.61	-0.34	4.39	50.55
Yaroslav Rybakov	7.59	4.31	3.28	-0.45	4.18	51.87
Mark Boswell	7.87	4.42	3.45	-0.20	4.32	51.37
Jaroslav Baba	7.28	3.27	4.01	-0.36	4.25	46.67
Nicola Ciotti	8.03	4.35	3.68	-0.48	4.40	50.07
Stefan Holm	8.11	4.73	3.38	-0.07	4.51	53.18
Vyacheslav Voronin	7.31	3.75	3.56	-0.20	4.23	49.92
Dracutin Topic	8.29	4.83	3.46	-0.64	4.36	51.54
Kyrikos Iannou	7.67	4.83	2.84	-0.17	4.26	56.34
Oskari Frösen	7.55	3.96	3.59	-0.24	4.12	48.91
Matt Hemingway	8.10	4.62	3.48	-0.40	4.18	50.23
Andriy Sokolovskyy	7.99	4.83	3.16	-0.32	4.06	52.10
average	7.78	4.31	3.47	-0.33	4.30	51.11
standard deviation	0.34	0.49	0.28	0.16	0.15	2.27

Table 4. The support times during the last two contacts and the flight time between them. The length of the last stride and it's projection angle to the y-axis (parallel with bar-line).

Name	stride length (m)	stride angle (°)	last (ms)	flight time (ms)	take-off (ms)
Yuriy Krymarenko	2.01	32.11	0.135	0.060	0.170
Victor Moya	1.92	24.78	0.150	0.050	0.200
Yaroslav Rybakov	2.16	31.82	0.140	0.040	0.190
Mark Boswell	2.29	24.27	0.140	0.050	0.185
Jaroslav Baba	2.03	37.30	0.160	0.080	0.200
Nicola Ciotti	2.06	27.15	0.130	0.060	0.175
Stefan Holm	1.99	25.60	0.145	0.055	0.150
Vyacheslav Voronin	2.11	26.94	0.155	0.050	0.190
Dracutin Topic	2.25	28.37	0.115	0.085	0.135
Kyrikos Iannou	1.97	26.36	0.175	0.060	0.155
Oskari Frösen	2.12	25.42	0.165	0.055	0.180
Matt Hemingway	1.99	25.66	0.160	0.070	0.180
Andriy Sokolovskyy	2.30	35.70	0.140	0.040	0.170
average	2.09	28.58	0.147	0.058	0.175
standard deviation	0.13	4.28	0.016	0.014	0.019

Table 5. The knee angles at the instant of the touch-down (TD) and the toe-off (TO) phases during the take-off and the lowest knee angle during the contact.

Name	knee TD	knee lowest	knee TO
Yuriy Krymarenko	171.94	146.23	177.97
Victor Moya	163.83	135.41	169.16
Yaroslav Rybakov	168.49	141.80	173.51
Mark Boswell	164.40	127.90	168.68
Jaroslav Baba	171.95	142.18	171.40
Nicola Ciotti	170.38	143.95	178.02
Stefan Holm	161.86	143.36	175.23
Vyacheslav Voronin	166.81	142.79	168.92
Dracutin Topic	173.90	163.50	177.96
Kyrikos Iannou	166.01	148.44	175.14
Oskari Frösen	172.41	144.70	175.27
Matt Hemingway	166.51	138.07	175.45
Andriy Sokolovskyy	167.38	150.07	174.36
average	168.14	143.72	173.93
standard deviation	3.73	8.26	3.40

Figure 1. Camera positions, co-ordinate system and the multi phase calibration area

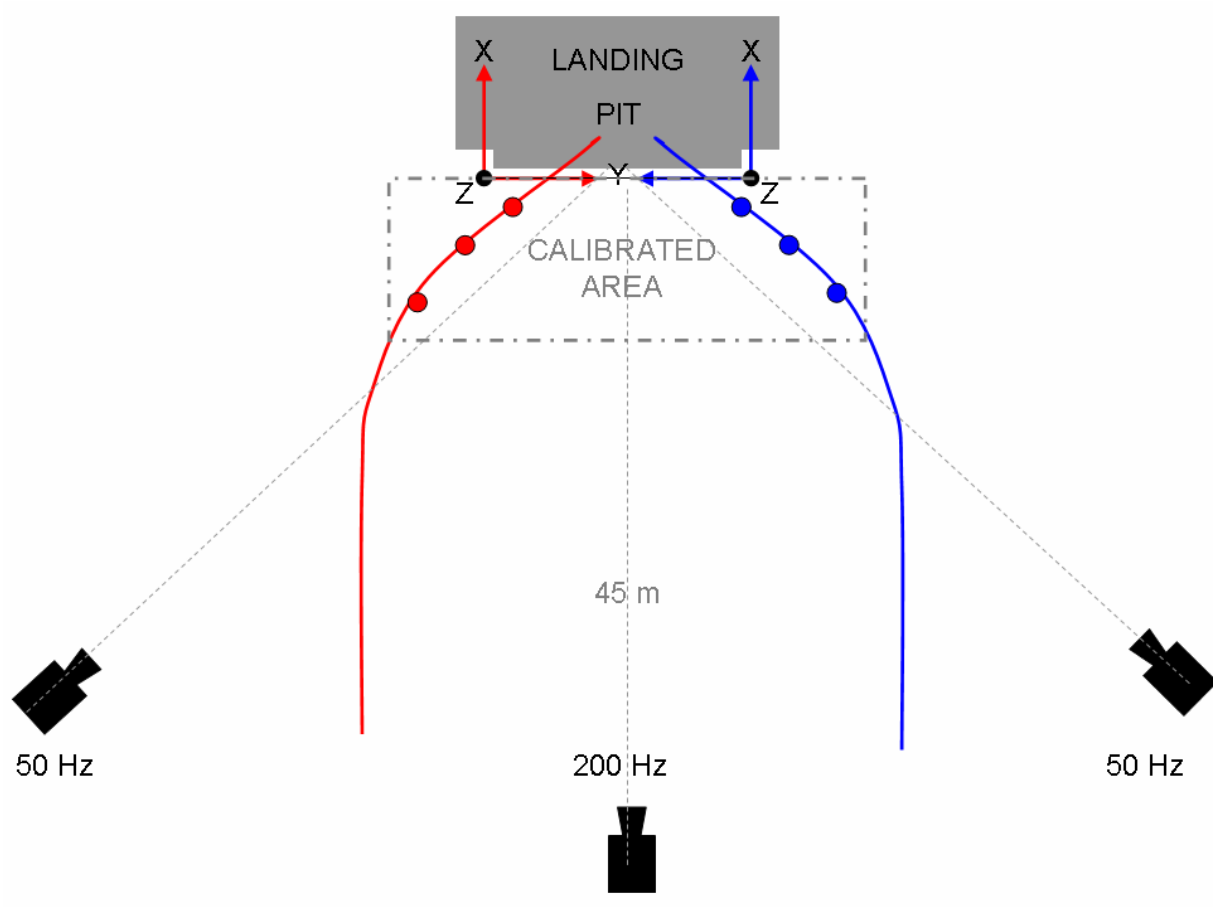


Figure 2. The overhead views of the paths of the centre of mass (COM) of the eight best finalists' curves. XY –co-ordinates of the two last contacts and COM locations during the touch-down and toe-off phases.

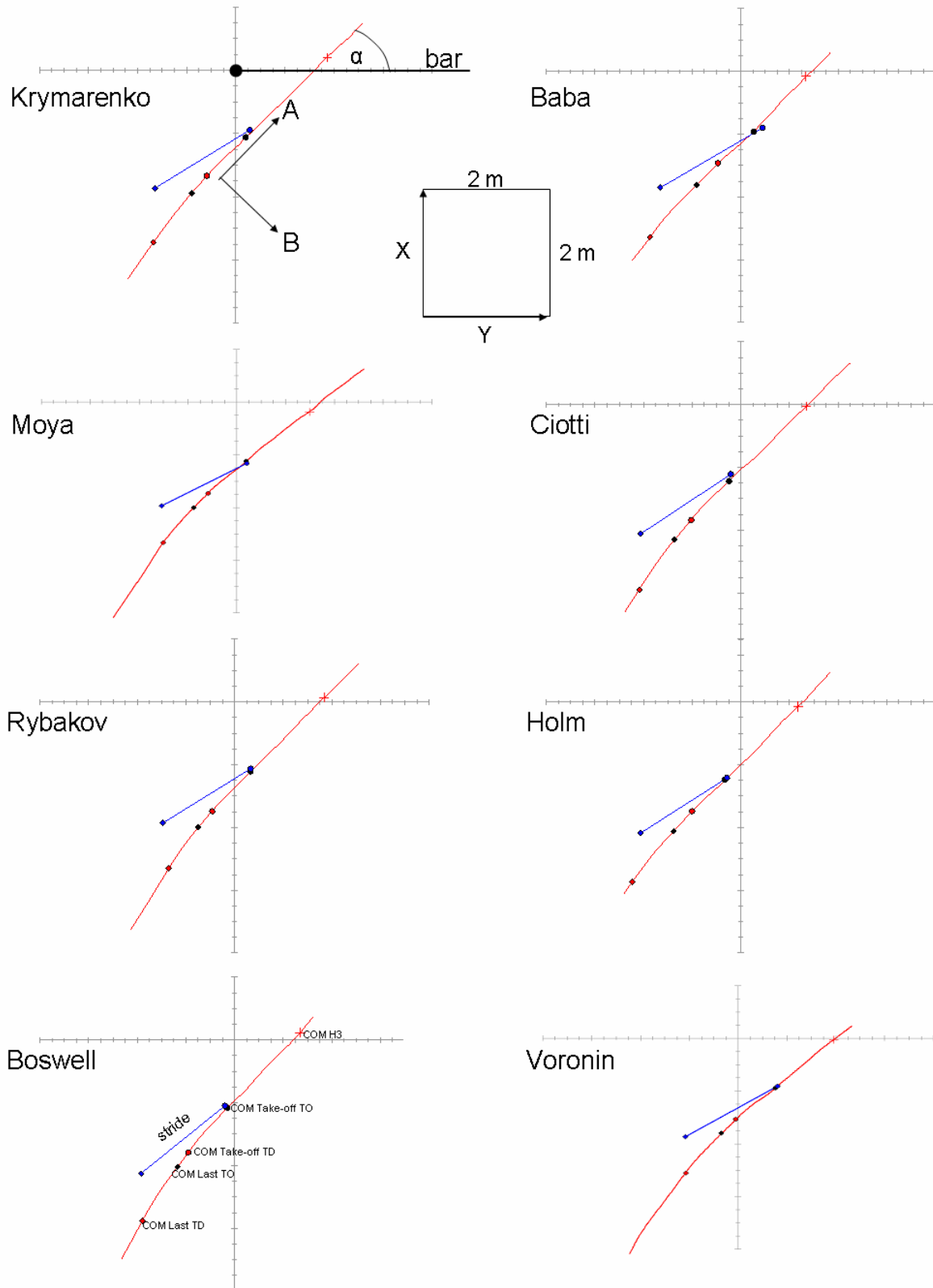
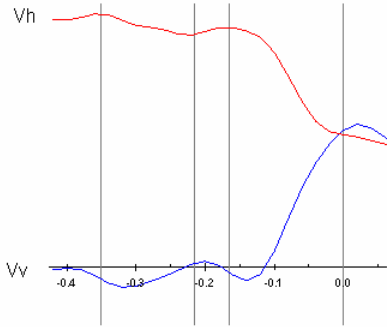
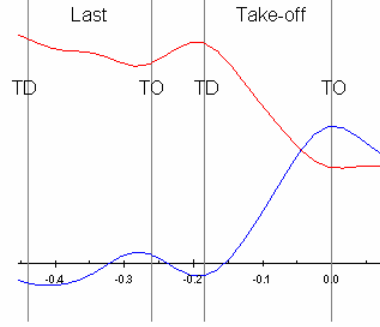


Figure 3. The horizontal ( $V_h$ ) and the vertical ( $V_v$ ) velocity curves of the eight best finalists.

Krymarengo

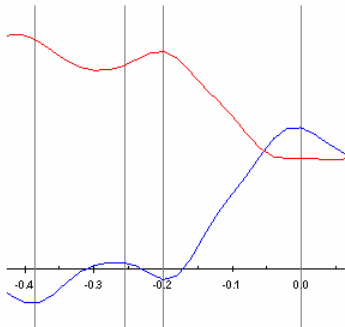


Baba

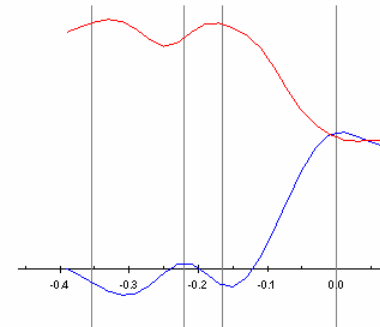


4 m/s

Moya

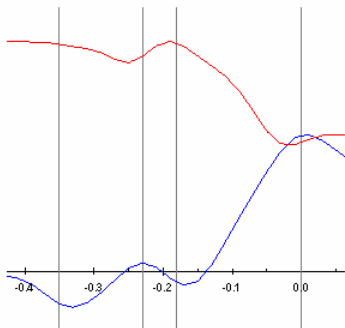


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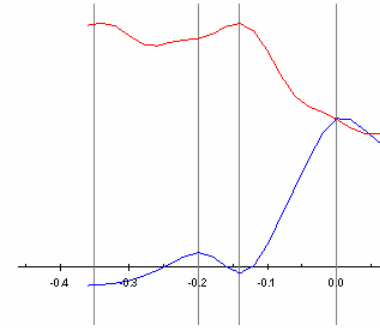


4 m/s

Rybakov

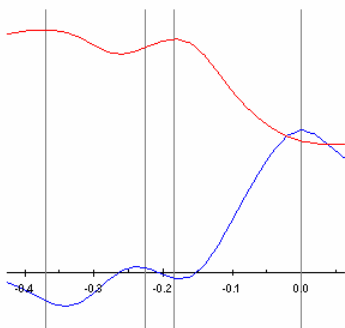


Holm

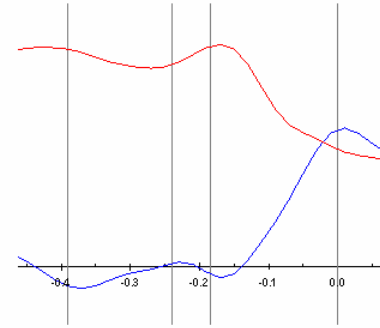


4 m/s

Boswell



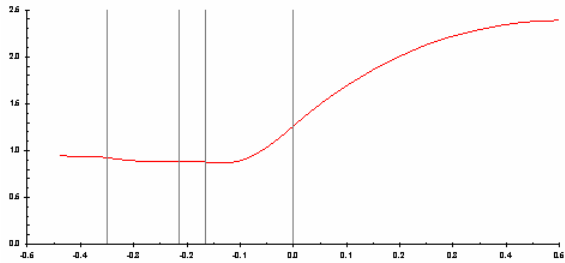
Voronin



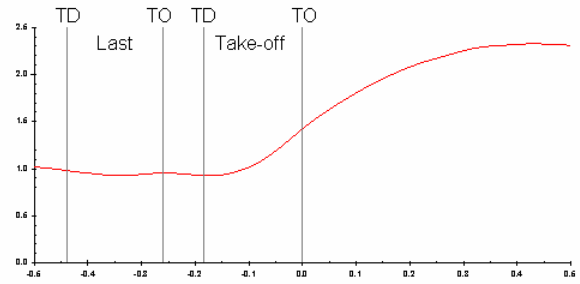
4 m/s

Figure 3. The height of the centre of mass during the last two contacts and the flight phase of the eight best finalists.

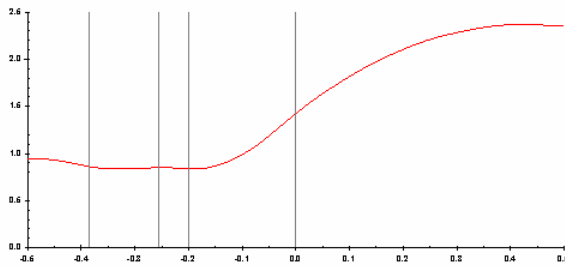
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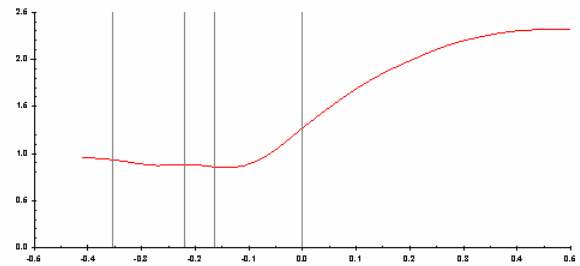
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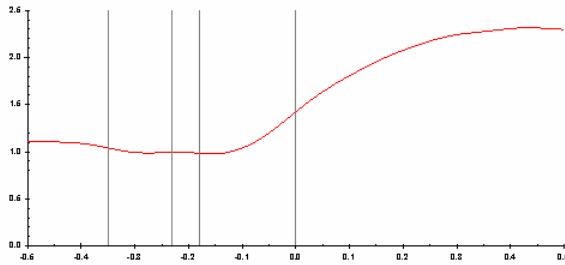
Moya



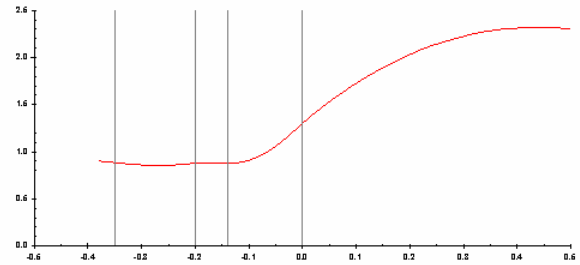
Ciotti



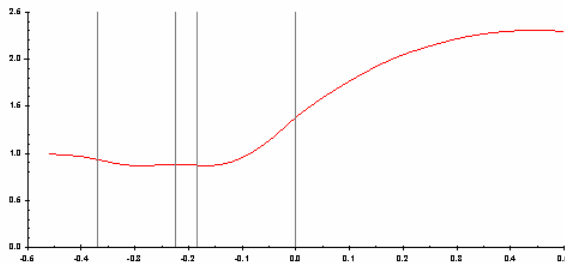
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