BIOMECHANICAL REPORT

FOR THE

IAAF World Championships

LONDON 2017

Pole Vault Men's

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INTRODUCTION

The men's pole vault final took place on the night of August 8th. The gold medal performance was achieved by Sam Kendricks on his third attempt at 5.95 m. Piotr Lisek achieved the silver medal by clearing 5.89 m in his first attempt but he and Renaud Lavillenie failed in their attempts at the 5.95 m mark. Lavillenie, the current world record holder, also cleared 5.89 m to secure the bronze medal and achieve a season's best performance. With only 0.06 m separating the clearance heights between gold and bronze medals, the competition to make the podium was strong. A national record was also achieved by Changrui Xue who finished 4th in the competition with a clearance of 5.82 m.

IAAF World Championships — London 4-13 August 2017

RESULTS

Pole Vault Men - Final

RECORDS	RESULT	NAME	COUNTRY	AGE	VENUE	DATE
World Record WR	6.16	Renaud LAVILLENIE	FRA	28	Donetsk (Sport Palace Druzhba)	15 Feb 2014
Championships Record CR	6.05	Dmitri MARKOV	AUS	26	Edmonton (Commonwealth Stadium)	9 Aug 2001
World Leading WL	6.00	Sam KENDRICKS	USA	25	Sacramento (Hornet Stadium), CA	24 Jun 2017

Area Record AR National Record NR Personal Best PB Season Best SB

8 August 2017 19:42 START TIME 22:03 END TIME — TEMPERATURE 16° C / 19° C — HUMIDITY 77 % / 56 %

PLACE	NAME	COUNTRY	DATE of BIRTH	ORDER	RESULT		5.50	5.65	5.75	5.82	5.89	5.95	6.01	6.06
1	Sam KENDRICKS	USA	7 Sep 92	7	5.95		O	O	O	O	O	XXO	Xr	
2	Piotr LISEK	POL	16 Aug 92	1	5.89		O	XXO	O	X-	O	XXX		
3	Renaud LAVILLENIE	FRA	18 Sep 86	11	5.89	SB	-	O	O	X-	XO	XX-	X	
4	Changrui XUE	CHN	31 May 91	3	5.82	NR	O	O	O	O	XXX			
5	Pawel WOJCIECHOWSKI	POL	6 Jun 89	10	5.75		O	O	XO	X-	XX			
6	Axel CHAPELLE	FRA	24 Apr 95	12	5.65		O	O	XXX					
7	Kurtis MARSCHALL	AUS	25 Apr 97	2	5.65		XO	O	XXX					
8	Shawnacy BARBER	CAN	27 May 94	8	5.65		XO	XXO	XXX					
9	Armand DUPLANTIS	SWE	10 Nov 99	5	5.50		O	XXX						
	Arnaud ART	BEL	28 Jan 93	4	NM		XXX							
	Raphael Marcel HOLZDEPPE	GER	28 Sep 89	6	NM		XXX							
	Jie YAO	CHN	21 Sep 90	9	NM		XXX							

Timing and Measurement by SEIKO AT-PV-M-f--A--.RS1..v1 Issued at 22:08 on Tuesday, 08 August 2017

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METHODS

Four vantage locations for camera placement were identified and secured. Each location had the capacity to accommodate two adjacent cameras placed on tripods. Two locations were situated on the broadcasting balcony along the home straight, one at the south media platform, and a final position was located at the end of the back straight. Three locations housed a Sony PXW-FS5 and a Canon EOS 700D. The final position was occupied by an additional Canon EOS 700D. All cameras were deployed to record each attempt during the men's pole vault final. The Sony PXW-FS5 cameras operating at 200 Hz (shutter speed: 1/1250; ISO: 2000; FHD: 1920x1080 px) recorded the last section of the runway to bar clearance. The Canon EOS 700D cameras operating at 60 Hz (shutter speed: 1/1250; ISO: 3200; SHD: 1280x720 px) recorded the entire trial from the start of the runway to landing.

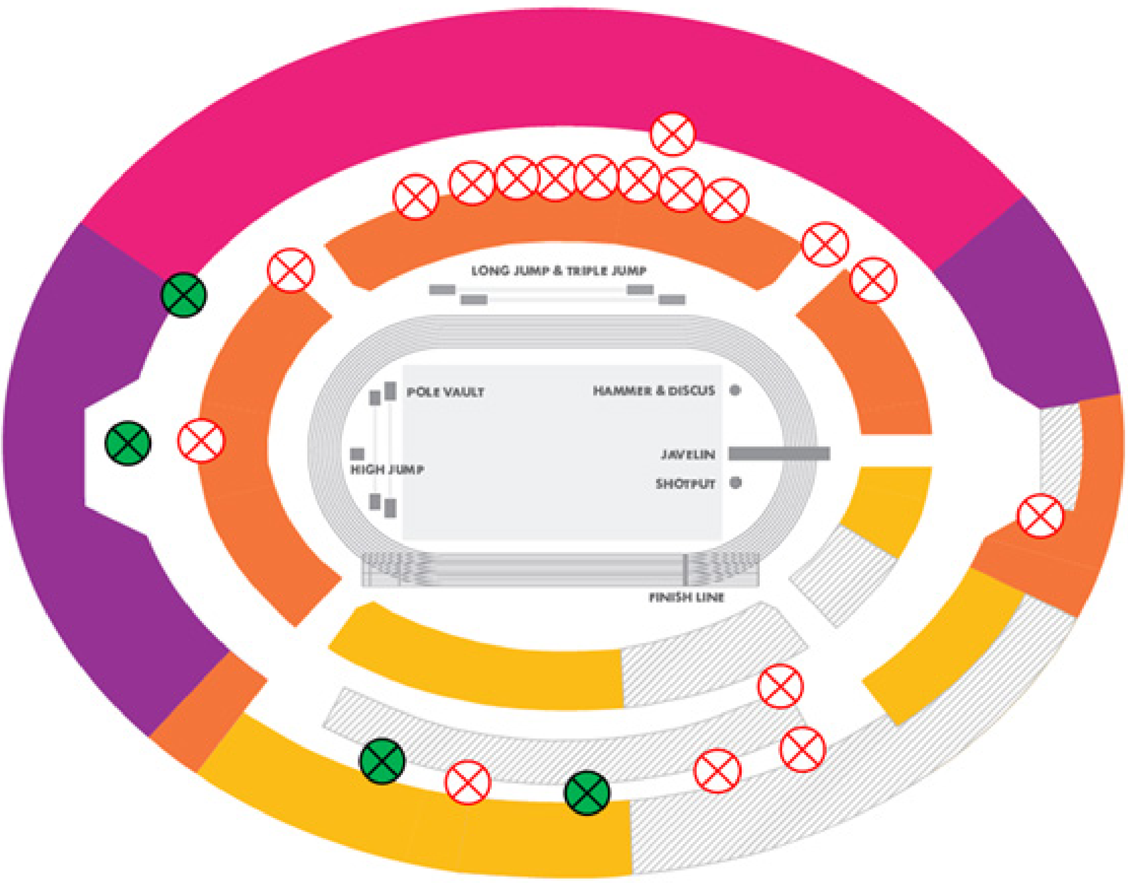


Figure 1. Camera positions for the men's pole vault final (shown in green).

Two separate calibration procedures were conducted after the competition. First, a rigid cuboid calibration frame was positioned on the runway over the plant box. This frame was then moved to a second position, away from the plant box to ensure an accurately defined volume that athletes would take off from and clear the crossbar in. This approach produced a large number of non-coplanar control points per individual calibrated volume and facilitated the construction of a specific global coordinate system. A further calibration was completed using vertical poles to accurately measure horizontal runway sections.

Figure 2. The calibration frame was constructed and recorded after the competition.

The best successful trial for each athlete was selected for analysis. For this reason, Arnaud Art, Raphael Marcel Holzdeppe and Jie Yao were not included. The video files were imported into SIMI Motion (SIMI Motion version 9.2.2, Simi Reality Motion Systems GmbH, Germany) for full body manual digitising. All digitising was completed by a single experienced operator to obtain kinematic data. An event synchronisation technique (synchronisation of four critical instants) was applied through SIMI Motion to synchronise the two-dimensional coordinates from each camera involved in the recording. Digitising took place during the approach, take-off and clearance. This commenced 15 frames before and finished 15 frames after various events of these phases to provide sufficient data for subsequent filtering. Each file was first digitised frame by frame and upon completion adjustments were made as necessary using the points over frame method, where each point (e.g. right knee joint) was tracked through the entire sequence.

The Direct Linear Transformation (DLT) algorithm was used to reconstruct the three-dimensional (3D) coordinates from individual camera's x and y image coordinates. Reliability of the digitising process was estimated by repeated digitising of one take-off with an intervening period of 48 hours. The results showed minimal systematic and random errors and therefore confirmed the high reliability of the digitising process. De Leva's (1996) body segment parameter models were used to obtain data for the whole body centre of mass. A recursive second-order, low-pass Butterworth digital filter (zero phase-lag) was employed to filter the raw coordinate data. The cut-off frequencies were calculated using residual analysis.

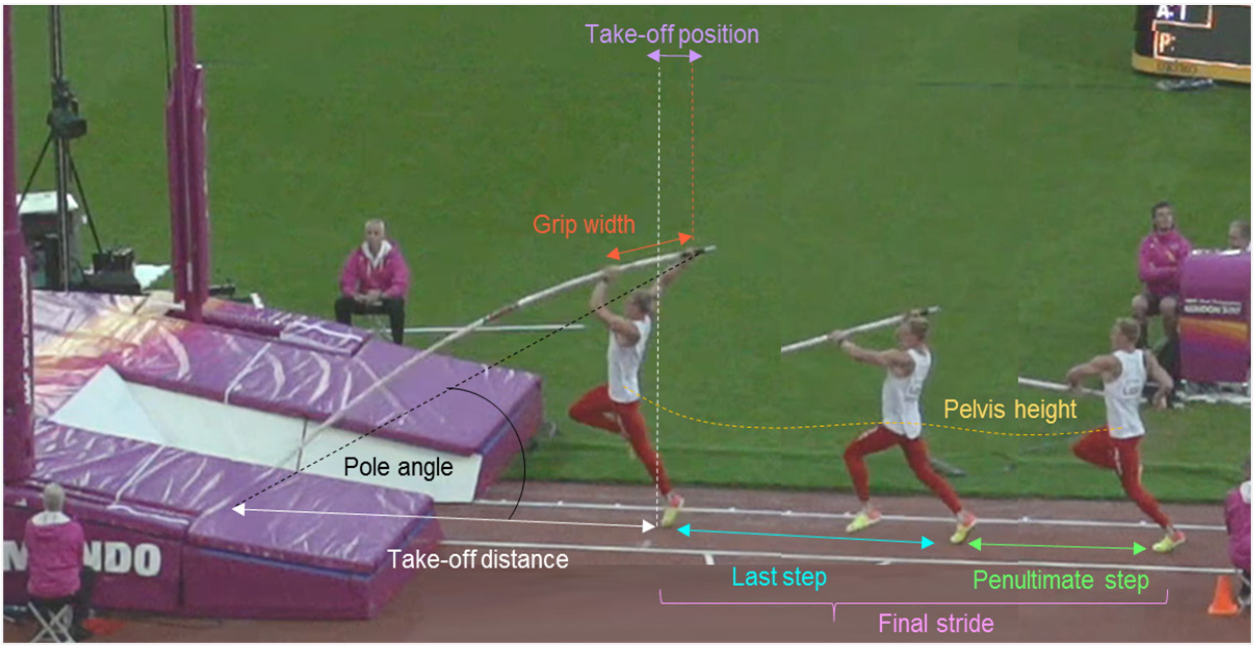


Figure 3. Final stride in the approach phase of the pole vault with visual definitions of the variables.

Table 1. Events selected to analyse the performance of the athletes.

Event	Definition
Take-off	The last point of contact when the foot leaves the runway.
Pole plant	The time instant when the pole makes contact with the box.
Pole release	The time instant when the upper grip releases the pole.

Table 2. Variables selected to describe the performance of the athletes.

Variable	Definition
Run up steps	The total number of steps completed on the runway to take-off, excluding any preparatory action.
Runway velocity	The mean horizontal velocity achieved during the mid-section of the runway (11-6 m away from the plant box).
Penultimate step length	The toe-off to toe-off distance of the step immediately before the last step.
Penultimate step velocity	The mean CM horizontal velocity during the step immediately before the last step.
Last step length	The toe-off to toe-off distance of the step immediately before take-off.
Last step velocity	The mean CM horizontal velocity during the step immediately before take-off.
Final stride length	The distance between the toe-off at the start of the penultimate step to the instant of take-off.
Take-off distance	The horizontal distance from the plant box to the foot tip at take-off.
Grip height	The distance between the lower tip of the pole and the athlete's upper grip.
Grip width	The distance between the upper and lower grip on the pole.
Take-off foot position	The horizontal distance between foot tip of the take-off leg and upper grip at the instant of take-off.
Take-off velocity	The resultant velocity of the CM at the instant of take-off.
Direction of travel	The angle between CM and horizontal at take-off and 5 frames after.

Pole angle	The angle between the pole chord and ground at take-off.
Ankle angle	The angle between the lower leg and foot segments.
Knee angle	The angle between the thigh and lower leg segments and considered to be 180° in the anatomical standing position.
Hip angle	The angle between the trunk and thigh segments and considered to be 180° in the anatomical standing position. Values greater than 180° indicates hyperextension.
Elbow angle	The angle between the upper and lower arm segments.
Shoulder angle	The angle between the upper arm and trunk segments and to be considered to be 0° in the anatomical standing position. Values greater than 180° indicates hyperextension.
Time on pole	The time between take-off and pole release.
Standing height	The vertical distance between the runway and the CM at take-off.
Swing height	The vertical distance between the CM at take-off and at pole release.
Push height	The vertical distance between the CM height at pole release and peak height.
CM clearance height	The vertical distance between the competition height and peak CM height.
Pelvis clearance height	The vertical distance between the competition height and pelvis height.
Pelvis horizontal distance	The horizontal distance from the cross bar to the pelvis at peak vertical height.
Vertical pelvis displacement	The vertical distance between the runway and the mid-point of the pelvis.
Shank angle	The angle of the shank segment relative to the runway.

Note: *CM = centre of mass.*

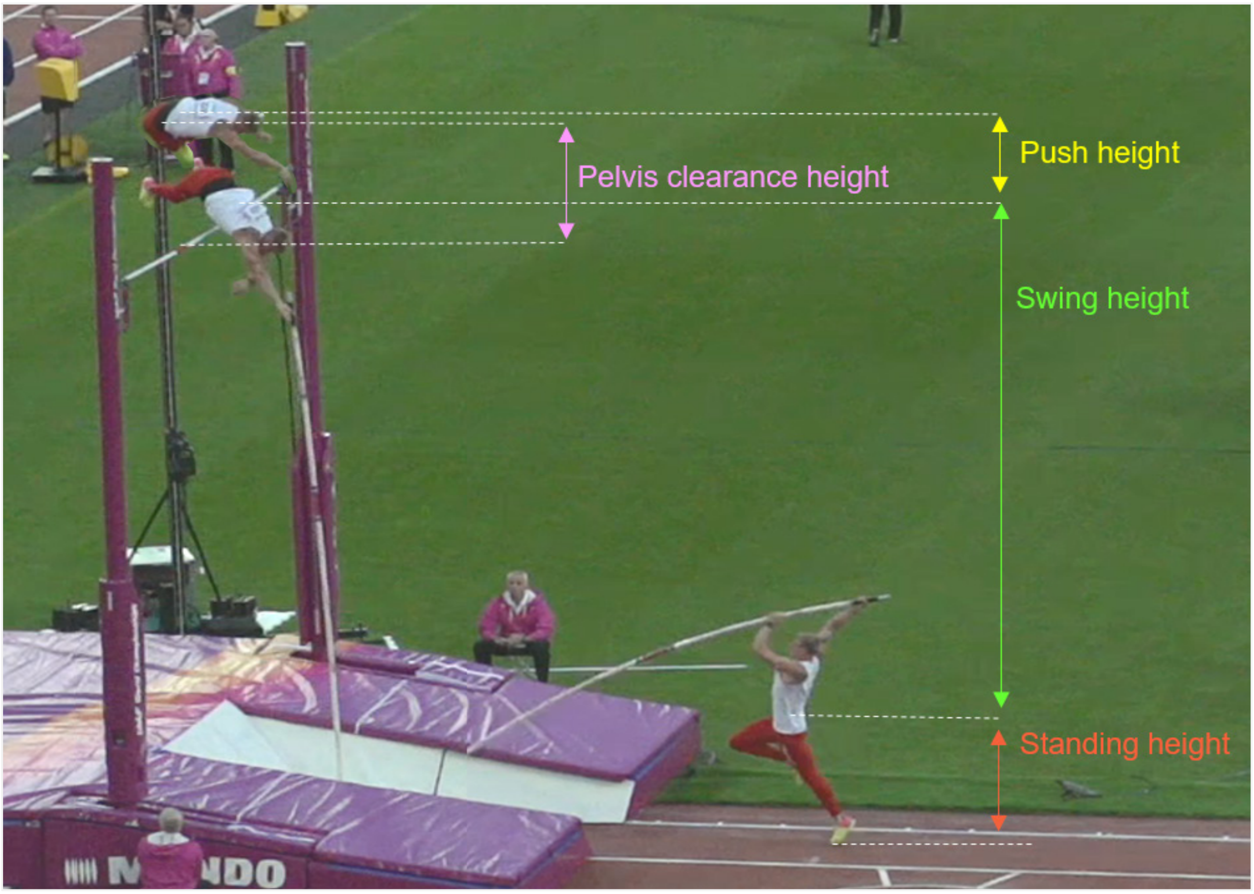


Figure 4. Visual definitions for partial height variables.

RESULTS

The mean age of the finalists was 24 years (Table 3). The finalists were younger compared to previous competitions; in Berlin 2009 (28 yrs), and Daegu 2011 (26.5 yrs). During the final, only one athlete exceeded his season's best performance (Table 2). The mean vault height for finalists in London 2017 was 5.75 m, 0.06 m lower than Daegu (5.81 m), but equal to the mean vault height in Berlin 2009 (5.75 m).

Table 3. Descriptive statistics for all finalists of the men's pole vault (mean ± SD).

Age (years)	Stature (m)	Mass (kg)
24 ± 4	1.83 ± 0.09	75.89 ± 7.93

Table 4. Competition results in relation to 2017 season's best (before the World Championships).

	Rank	SB 2017 (m)	Official Height (m)	Difference (%)
KENDRICKS	1	6.00	5.95	−0.83
LISEK	2	6.00	5.89	−1.83
LAVILLENIE	3	6.16	5.89	−4.38
XUE	4	5.70	5.82	+2.11
WOJCIECHOWSKI	5	5.93	5.75	−3.04
CHAPELLE	6	5.80	5.65	−2.59
MARSCHALL	7	5.73	5.65	−1.40
BARBER	8	5.83	5.65	−3.09
DUPLANTIS	9	5.90	5.50	−6.78

Table 5 shows the results for number of steps, runway velocity (m/s), and take-off distance (m). Mean runway velocity was 0.10 m/s faster in London (9.36 m/s), compared to Daegu (9.26 m/s) and by 0.18 m/s compared to mean runway velocities achieved in Berlin 2009 (9.18 m/s). The mean take-off distance was shorter than both Daegu (4.44 m) and Berlin (4.22 m).

Table 5. Number of run-up steps, runway velocity in section 11-6 m and take-off distance.

	Steps	Runway velocity (m/s)	Take-off distance (m)
KENDRICKS	20	9.23	4.02
LISEK	16	9.33	4.29
LAVILLENIE	20	9.49	4.45
XUE	18	9.33	4.21
WOJCIECHOWSKI	16	9.23	3.97
CHAPELLE	24	9.44	3.56
MARSCHALL	18	9.13	4.37
BARBER	20	9.49	4.31
DUPLANTIS	18	9.53	3.60

Presented above are traditionally reported variables for analysing pole vault performance. The next page provides a more detailed analysis of the final steps on the runway. This includes mean velocity during the step, and the step length.

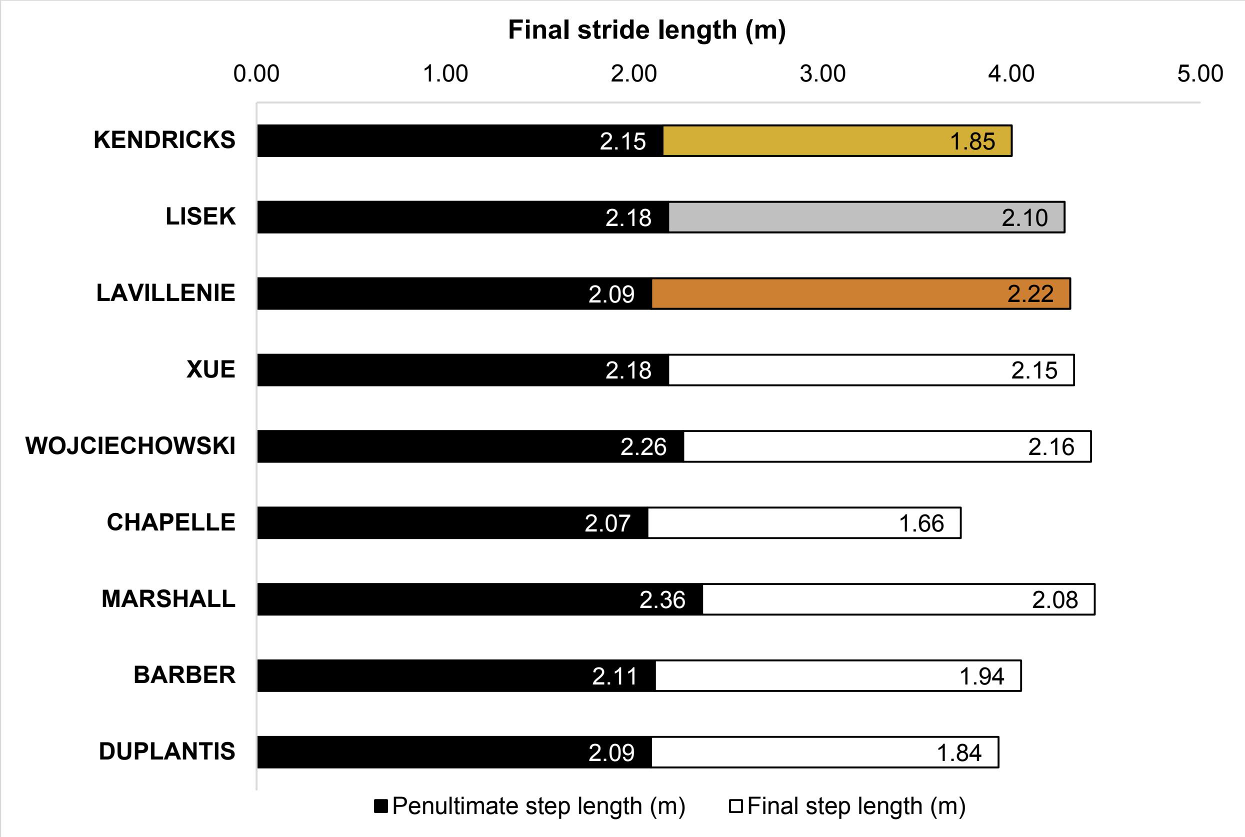


Figure 5. Contribution of the last two steps to final stride length.

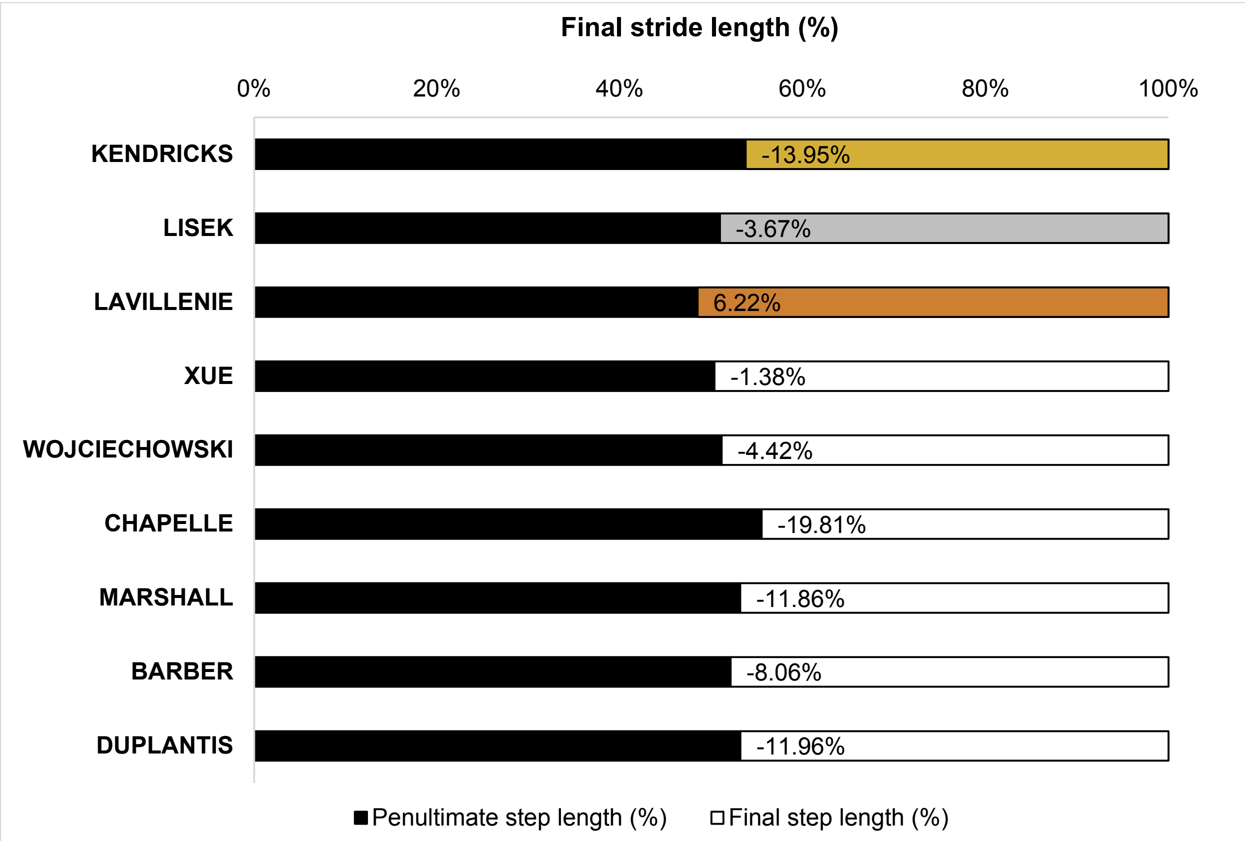
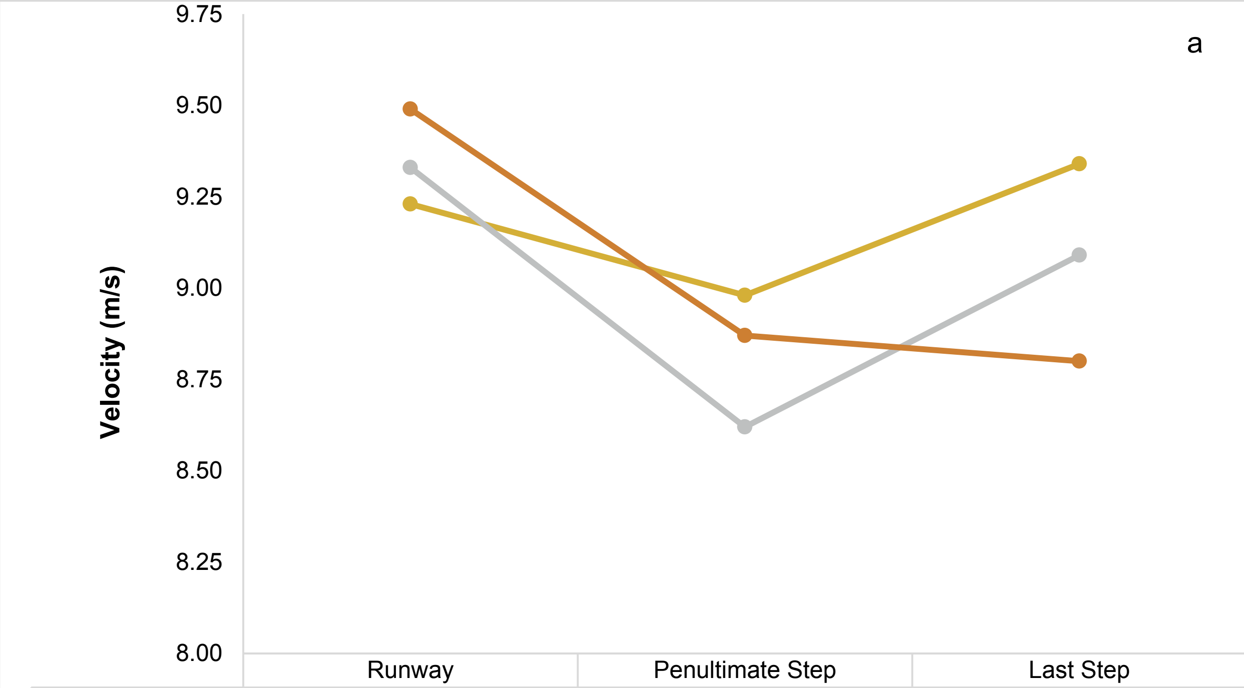
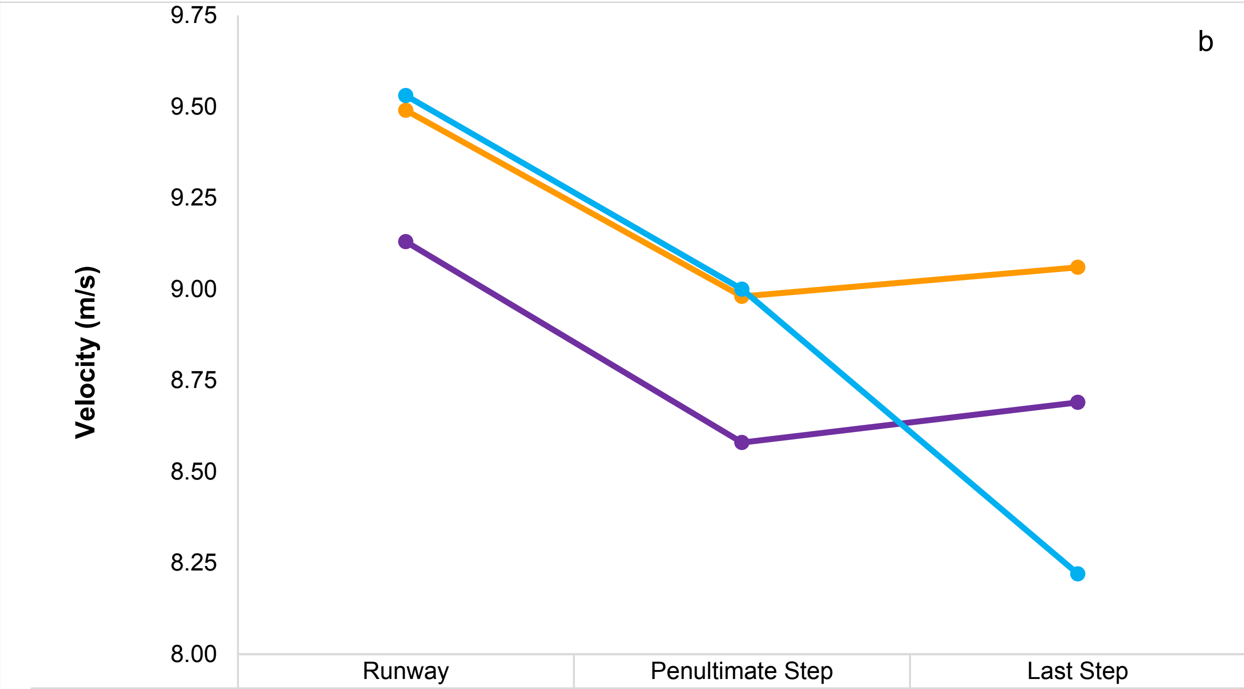


Figure 6. Relative contribution of the last two steps to final stride length. The percentage change is also displayed. A negative number indicates that the final step was shorter than the penultimate step.

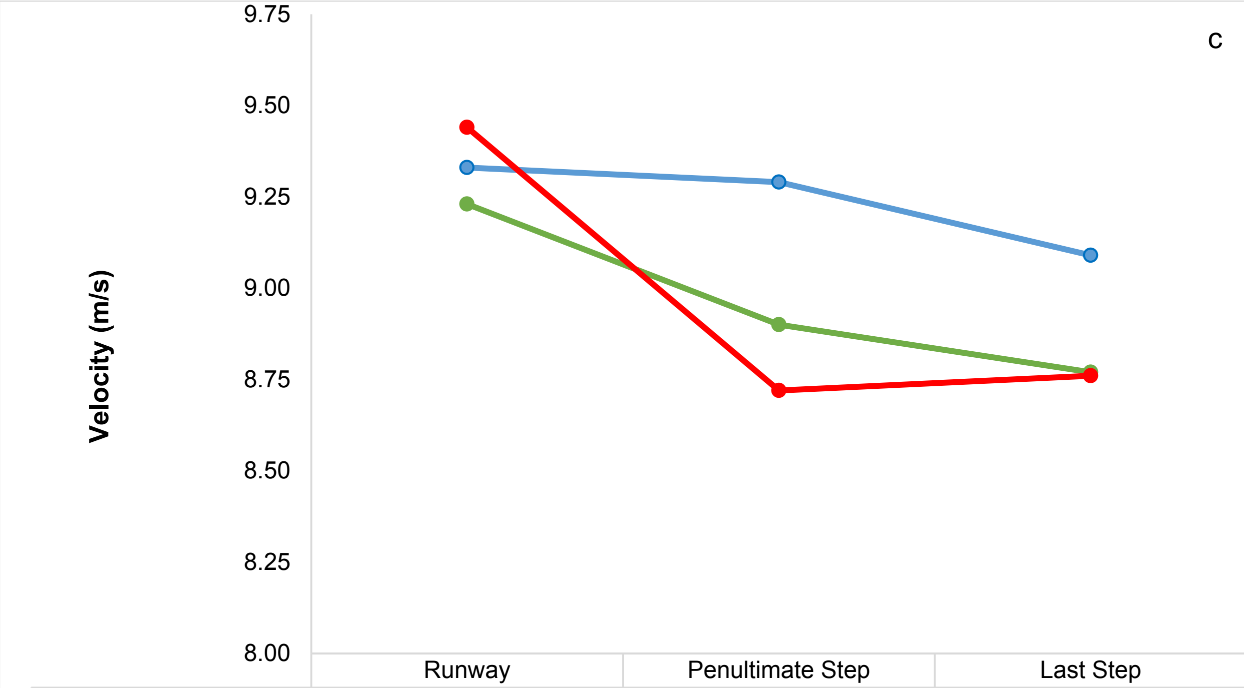
The following three graphs depict velocity profiles for each of the finalists. Mean horizontal velocity on the runway (11-6 m), during the penultimate, and last steps is presented.



	Runway	Penultimate Step	Last Step
KENDRICKS	9.23	8.98	9.34
LISEK	9.33	8.62	9.09
LAVILLENIE	9.49	8.87	8.80



	Runway	Penultimate Step	Last Step
MARSHALL	9.13	8.58	8.69
BARBER	9.49	8.98	9.06
DUPLANTIS	9.53	9.00	8.22



	Runway	Penultimate Step	Last Step
XUE	9.33	9.29	9.09
WOJCIECHOWSKI	9.23	8.90	8.77
CHAPELLE	9.44	8.72	8.76

Figure 7 a, b, c. Velocity profiles of all athletes.

On the following pages, Figures 8 and 9 illustrate variables relating to handgrip at take-off. More specifically, Figure 8 illustrates the position of the take-off foot with respect to upper grip position. Negative values indicate the foot was in front of the upper grip (under), and positive values indicate the foot was behind (out). Figure 9 shows the variety of grip widths and grip heights adopted by the competitors during the final.

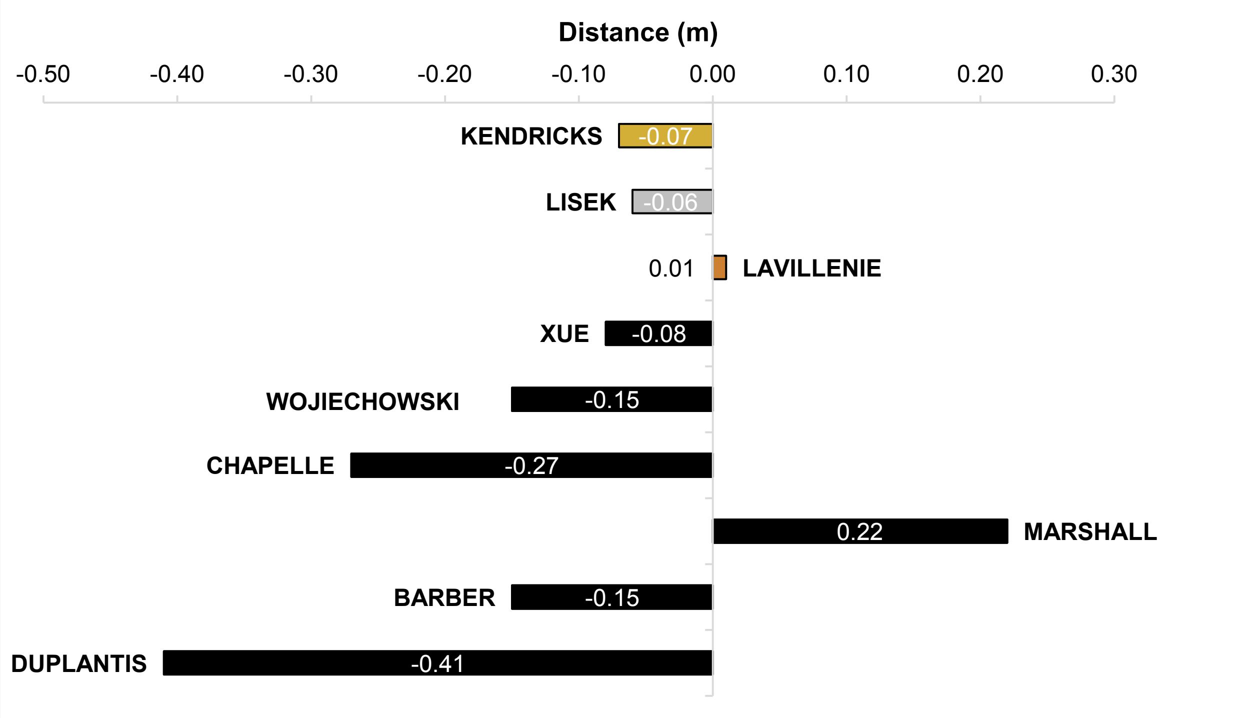


Figure 8. Take-off foot position (relative to upper grip position).

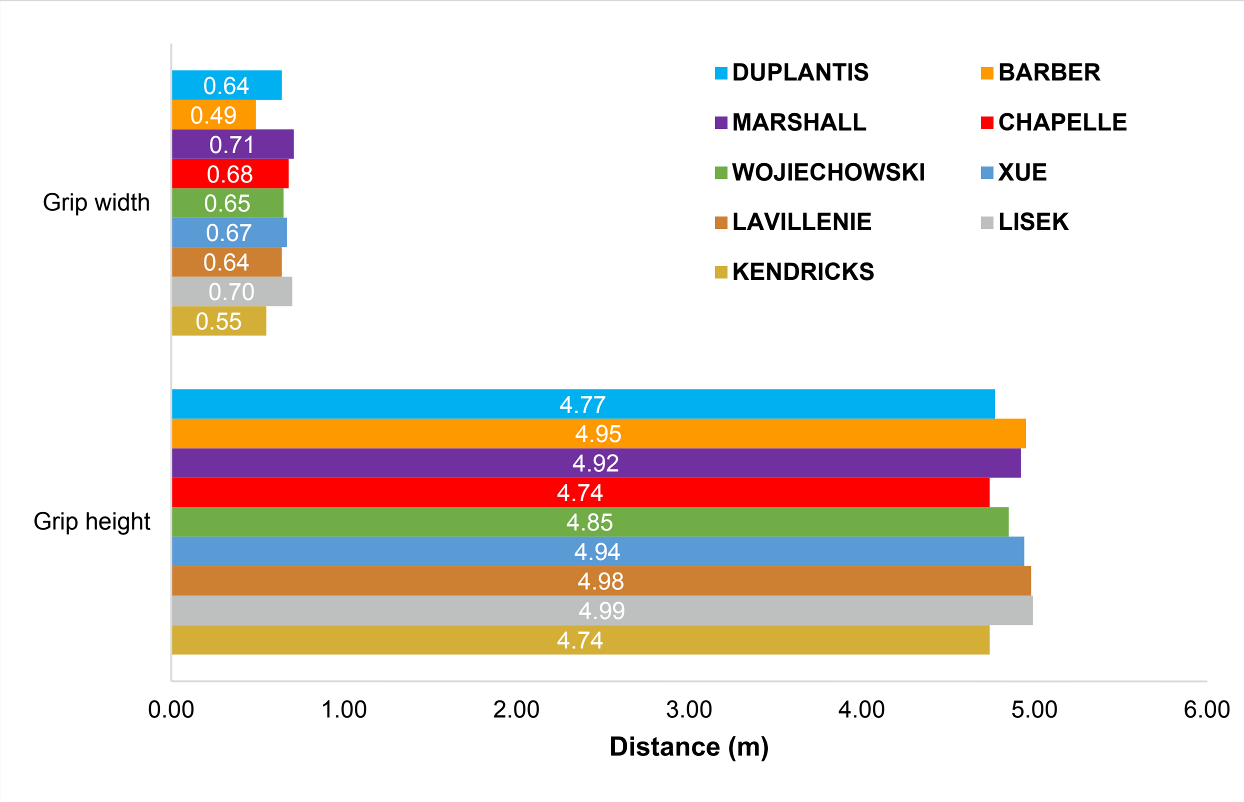


Figure 9. Grip positions for each of the finalists.

The parameters in Table 6 below describe the resultant velocity, direction of travel and the angle between the pole chord and runway at take-off. The following two pages describe joint angles at take-off for both the left and right sides of the body.

Table 6. Take-off parameters.

	Resultant take-off velocity (m/s)	Direction of travel (°)	Pole angle (°)
KENDRICKS	9.37	15	29
LISEK	8.31	24	29
LAVILLENIE	8.24	15	26
XUE	8.56	15	28
WOJCIECHOWSKI	7.43	20	30
CHAPELLE	8.14	21	30
MARSCHALL	8.91	14	28
BARBER	8.00	15	27
DUPLANTIS	7.81	17	30

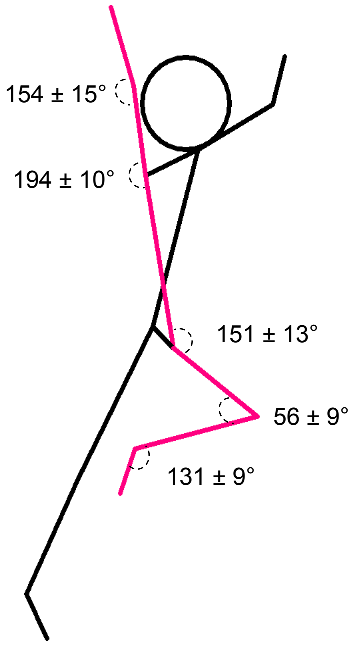


Figure 10. Mean ± standard deviation joint angles at take-off for the right hand side.

All of the athletes in the final used their right leg to drive, and right arm for upper grip (pink). The joint angles for the individual athletes are displayed in Table 7. For illustration purposes Figure 10 displays a take-off posture, with mean and standard deviation angles for all of the finalists. This does not represent any finalist's posture.

Table 7. Details of joint angles of the drive leg and upper grip arm at the instant of take-off.

	Right ankle (°)	Right knee (°)	Right hip (°)	Right elbow (°)	Right shoulder (°)
KENDRICKS	136	57	155	147	184
LISEK	122	55	147	156	191
LAVILLENIE	119	66	148	164	202
XUE	134	53	136	170	194
WOJCIECHOWSKI	149	57	140	160	187
CHAPELLE	134	68	162	151	191
MARSCHALL	130	40	147	164	198
BARBER	125	61	145	118	214
DUPLANTIS	129	46	178	159	185

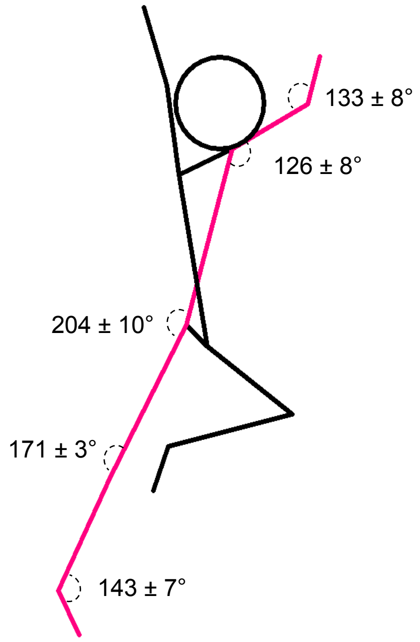


Figure 11. Mean ± standard deviation joint angles at take-off for the left hand side.

All of the athletes in the final used their left leg for take-off, and left arm for lower grip (pink). The joint angles for the individual athletes are displayed in Table 8. For illustration purposes Figure 11 displays a take-off posture, with mean and standard deviation angles for all of the finalists. This does not represent any finalist's posture.

Table 8. Details of joint angles of the take-off leg and lower grip arm at the instant of take-off.

	Left ankle (°)	Left knee (°)	Left hip (°)	Left elbow (°)	Left shoulder (°)
KENDRICKS	140	172	195	132	141
LISEK	128	167	199	118	116
LAVILLENIE	137	170	198	129	118
XUE	142	168	200	132	119
WOJCIECHOWSKI	147	170	205	141	124
CHAPELLE	150	172	205	141	133
MARSCHALL	145	174	229	138	131
BARBER	151	176	196	125	124
DUPLANTIS	147	174	205	139	127

Table 9. Absolute contributions to height in the pole vault. H_s represents swing height; H_p represents push height; H_{cc} represents CM clearance height and H_{pc} represents pelvis clearance height.

	Standing height (m)	Official height (m)	Time on pole (s)	Height (m)	
KENDRICKS	1.24	5.95	1.29	H_s	4.47
				H_p	0.29
				H_{cc}	0.05
				H_{pc}	0.35
LISEK	1.27	5.89	1.13	H_s	4.55
				H_p	0.20
				H_{cc}	0.13
				H_{pc}	0.23
LAVILLENIE	1.21	5.89	1.37	H_s	4.67
				H_p	0.23
				H_{cc}	0.22
				H_{pc}	0.32
XUE	1.26	5.82	1.18	H_s	4.50
				H_p	0.26
				H_{cc}	0.19
				H_{pc}	0.32
WOJCIECHOWSKI	1.26	5.75	1.31	H_s	4.58
				H_p	0.08
				H_{cc}	0.17
				H_{pc}	0.44
CHAPELLE	1.15	5.65	0.73	H_s	3.99
				H_p	0.65
				H_{cc}	0.14
				H_{pc}	0.39
MARSCHALL	1.27	5.65	1.54	H_s	4.41
				H_p	0.04
				H_{cc}	0.07
				H_{pc}	0.34
BARBER	1.25	5.65	1.52	H_s	4.49
				H_p	0.02
				H_{cc}	0.10
				H_{pc}	0.35
DUPLANTIS	1.20	5.50	1.37	H_s	4.42
				H_p	0.12
				H_{cc}	0.23
				H_{pc}	0.50

On the previous page, Table 9 provides the absolute contributions to height in the men's final. The relative contributions to height are provided in Figure 12 below, where 100 % indicates official bar height.

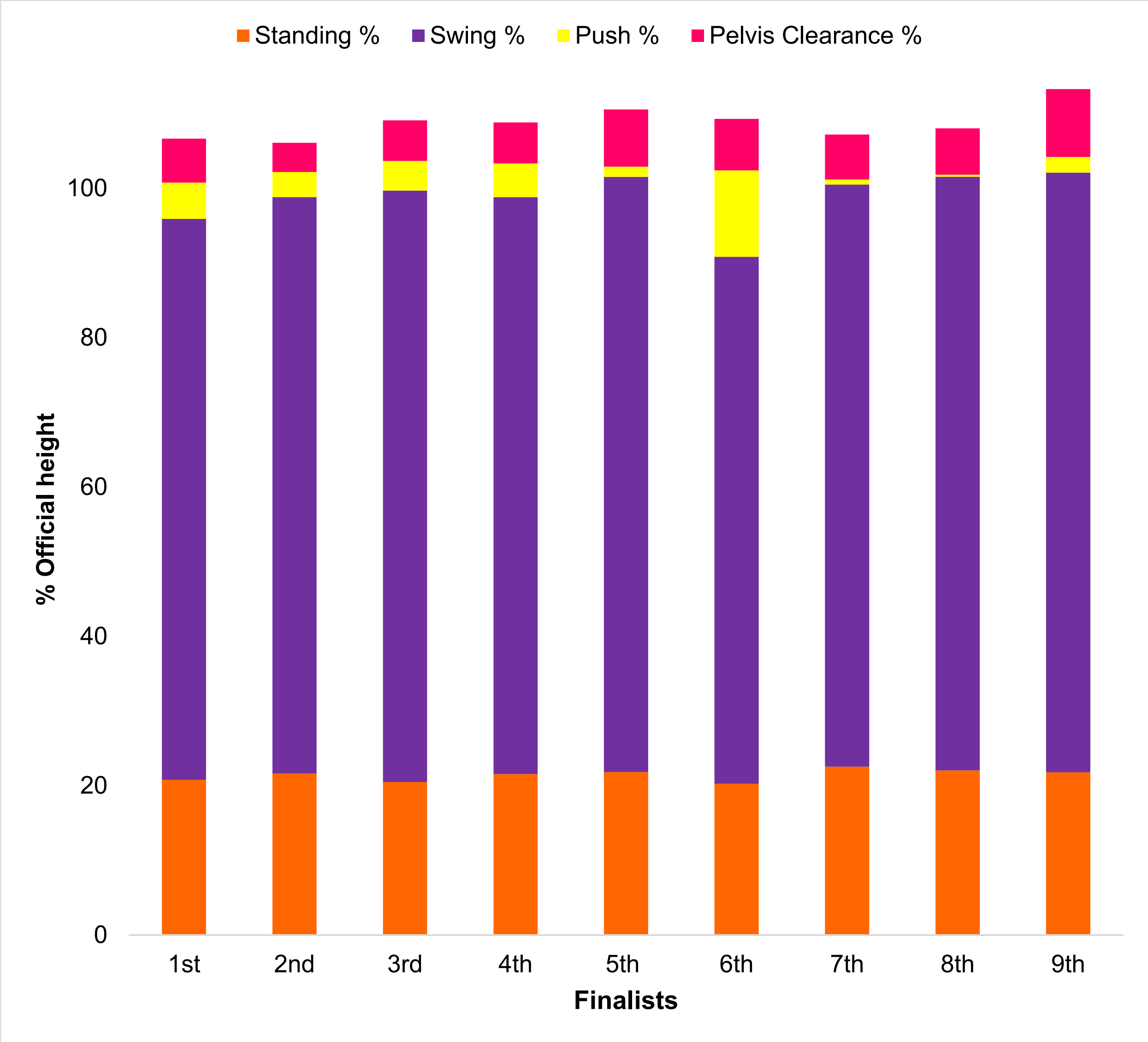


Figure 12. Relative contributions to height in the pole vault expressed as a percentage of the official bar height.

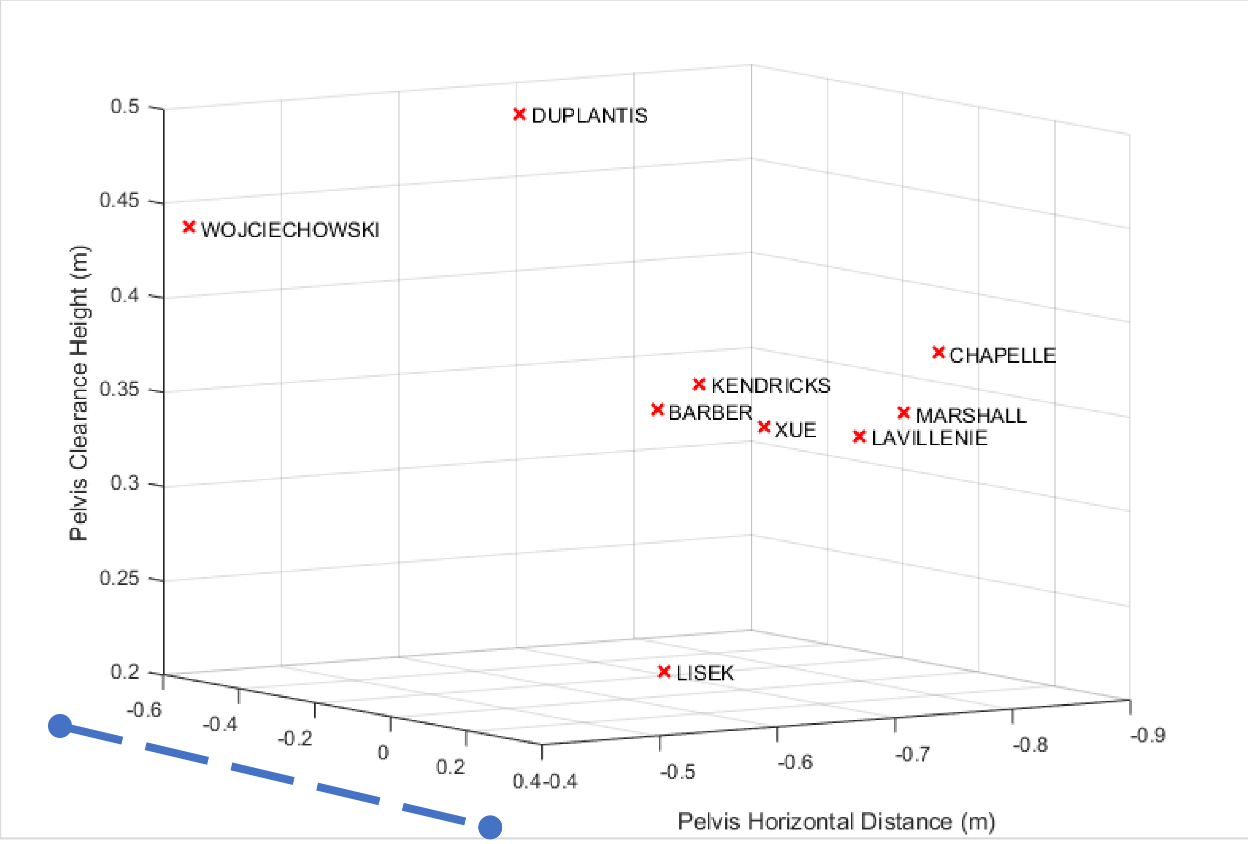


Figure 13. A 3D scatter graph to illustrate peak pelvis position in relation to the competition crossbar.

Figure 13 shows the vertical clearance height and corresponding horizontal positions of the pelvis at the apex of the vault. A visual representation of the crossbar has been included for reference (blue dashed line), where the centre of the crossbar is the origin of the three axes. The pelvis horizontal distance shows the penetration towards the pit, whilst the axis parallel to the crossbar shows the mediolateral location. The red crosses represent the position of the pelvis relative to the individual competition bar height for each of the finalists. This ranged between 5.50 – 5.95 m.

Further key variables

Through discussion with the coaching collaborator and trying to better understand the techniques employed, the following two variables were chosen for analysis within the medallists. The first variable (Figure 14) shows the path of the pelvis throughout the last three steps to appreciate the running technique in these steps and provide an indication of how much bounce the running pattern had. In this graph time has been normalised to 100% and pelvis height has been standardised to its height at the beginning of the third last step. Table 10 displays the lower leg position (shank angle) during the approach at three instants (touchdown, pole plant and take-off) to indicate how the take-off leg was oriented.

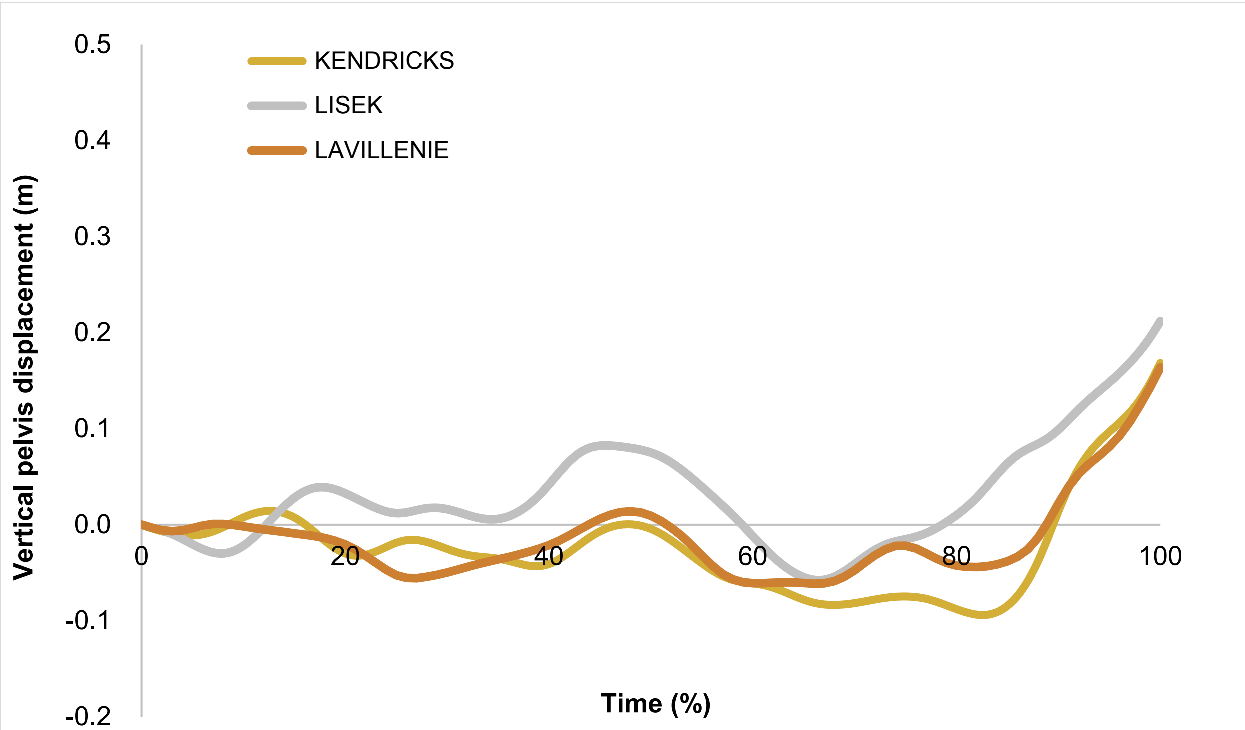


Figure 14. Fluctuations in pelvis height during the last 3 steps for the medallists.

Table 10. Shank angle of the take-off leg at touchdown, pole plant and take-off relative to the ground for the medallists.

	Touchdown (°)	Pole plant (°)	Take-off (°)
KENDRICKS	113	67	67
LISEK	109	60	55
LAVILLENIE	111	61	60

COACH'S COMMENTARY

In an event as technically complex as the pole vault, there are many factors that can contribute to the potential height of the vaulter. As anticipated, I found very few attributes critical to performance when reviewing these data. Each athlete has a unique composition, with slightly different strengths and weaknesses. Individual, technical adaptations to minimise energy loss throughout the vault means there is not just a single criterion alone responsible for success, and this is supported by the data presented.

This being said, some data did stand out between the medallists of the men's competition. First, Kendricks did not have the fastest velocity between 11-6 m of the runway, but did have the fastest velocity into the last step. He also had the highest resultant velocity at take-off. Kendricks's last step was shorter than his penultimate step, and the difference between the two was one of the greatest in the competitive field.

The medallists' take-off position was shorter than the other competitors in the field, meaning the hand of the upper grip was more in line with the take-off foot at take-off. Most of the other athletes had a more exaggerated, 'under' take-off position. Individual variations in handgrip width and grip height can also be seen in the data.

In addition to these findings, I have also observed some data that do not necessarily result in a higher performance but are noteworthy. Interestingly, there was a negative correlation between time on pole and height gained through the push off ($r = -0.92$), meaning the less time the male athletes were on the pole, the higher the resulting push-off would be. This was not the case in the women's data ($r = -0.06$) because of the smaller contribution the push provides to total height.

As coaches, we have to maximise the athlete's ability to not only jump high but also penetrate into the pit. Pole vault is a system of energy; you cannot have one piece of the system far greater than the other – it has to transfer across the system as a whole. This is achieved through posture, position and pole drop on the runway. Outside of these principles, I believe that because of the variety in jumping styles these data should not be used to 'compare' the physical or technical attributes of the different athletes. Instead, these data would ideally be used by the individual athletes and coaches to assess if, and how, the changes made throughout are transferred into the vault.

CONTRIBUTORS

Helen Gravestock is a Lecturer in Sport and Exercise Biomechanics at Leeds Beckett University, and is a BASES probationary sport and exercise scientist in biomechanics. Helen has a First Class Honours degree in BSc Sport and Exercise Science, and an MSc in Applied Sport Science from the University of Worcester. Helen's research interests include the biomechanics of race walking, gait and 3D motion capture. Previously, Helen has provided applied biomechanical support to British Athletics and British Gymnastics during competition.

Dr Athanassios Bissas is the Head of the Biomechanics Department in the Carnegie School of Sport at Leeds Beckett University. His research includes a range of topics but his main expertise is in the areas of biomechanics of sprint running, neuromuscular adaptations to resistance training, and measurement and evaluation of strength and power. Dr Bissas has supervised a vast range of research projects whilst having a number of successful completions at PhD level. Together with his team he has produced over 100 research outputs and he is actively involved in research projects with institutions across Europe.

Mitchell Krier is the coach of Olympic and world champion, Katerina Stefanídi. He studied exercise science and spent many years pole vaulting under the guidance of Cranston Hysong, father and coach of Olympic champion Nick Hysong. He also spent three additional years training and coaching under Nick Hysong. After coaching Stefanídi to an undefeated season in 2017, he was named International coach of the year in the pole vault at the national pole vault summit.