IAAF World Championships
LONDON 2017

BIOMECHANICAL REPORT

FOR THE

IAAF World Championships
LONDON 2017

400 m Women's

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INTRODUCTION

In the highly anticipated women's 400 m final on the evening of Wednesday 9th August, Phyllis Francis upset the form book and secured one of the surprise gold medals of the championships with a lifetime best performance despite poor weather conditions. In similar circumstances to the 2016 Olympic final, Shaunae Miller-Uibo led the defending champion Allyson Felix into the home straight. Although Felix could not produce her trademark finish and began to run out of steam, it was Miller-Uibo who faltered 30 m from the line eventually finishing fourth in 50.49 s. Francis took full advantage, passing Felix at 370 m and then the stricken Miller-Uibo at 380 m to secure gold in 49.92 s. Silver went to the impressive 19-year-old Bahraini Salwa Eid Naser. The time of 50.06 s surpassed her lifetime best performance during the semi-finals (50.08 s) where she again overtook Felix in the closing stages. Felix did however take the bronze in a time of 50.08 s, and at the same time equalled the record of the most successful athletes at the World Championships, alongside Usain Bolt and Merlene Ottey.

IAAF World Championships — London, 4-13 August 2017

RESULTS

400 Metres Women - Final

RECORDS	RESULT	NAME	COUNTRY	AGE	VENUE	DATE
World Record WR	47.60	Marita KOCH	GDR	28	Canberra (Bruce Stadium)	6 Oct 1985
Championships Record CR	47.99	Jarmila KRATOCHVÍLOVÁ	TCH	32	Helsinki (Olympic Stadium)	10 Aug 1983
World Leading WL	49.65	Allyson FELIX	USA	32	London (Olympic Stadium)	9 Jul 2017

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

9 August 2017 21:50 START TIME 15° C TEMPERATURE 88 % HUMIDITY

PLACE	NAME	COUNTRY	DATE of BIRTH	LANE	RESULT		REACTION	Fn
1	Phyllis FRANCIS	USA	4 May 92	6	49.92	PB	0.196	
2	Salwa Eid NASER	BRN	23 May 98	4	50.06	NR	0.203	
3	Allyson FELIX	USA	18 Nov 85	5	50.08		0.184	
4	Shaunae MILLER-UIBO	BAH	15 Apr 94	7	50.49		0.160	
5	Shericka JACKSON	JAM	16 Jul 94	2	50.76		0.194	
6	Stephenie Ann MCPHERSON	JAM	25 Nov 88	8	50.86		0.162	
7	Kabange MUPOPO	ZAM	21 Sep 92	9	51.15		0.184	
8	Novlene WILLIAMS-MILLS	JAM	26 Apr 82	3	51.48		0.272	

Timing and Measurement by SEIKO AT-400-W-f--1--.RS1..v1 Issued at 21:54 on Wednesday, 09 August 2017

Official Partners

METHODS

Eleven vantage locations for camera placement were identified and secured. Six of these were dedicated to the home straight and the additional five were strategically positioned around the stadium (Figure 1). Each of the home straight locations had the capacity to accommodate up to five cameras placed on tripods in parallel. Five locations were situated on the broadcasting balcony along the home straight (from the 300 m line to the 390 m line) whilst the sixth location was located within the IAAF VIP outdoor area overlooking the finish line from a semi-frontal angle. Two separate calibration procedures were conducted before and after each competition. First, a series of nine interlinked training hurdles were positioned every 10 m along the home straight ensuring that the crossbar of each hurdle, covered with black and white tape, was aligned with the track's transverse line (Figure 2). These hurdles were also positioned across all nine lanes on the track markings for the 100, 200 and 300 m intervals. Second, a rigid cuboid calibration frame was positioned on the running track between the 347-metre mark and the 355.5-metre mark (from the starting line) multiple times over discrete predefined areas along and across the track to ensure an accurate definition of a volume within which athletes were achieving high running speeds (Figure 3). This approach produced a large number of non-coplanar control points per individual calibrated volume and facilitated the construction of bi-lane specific global coordinate systems.

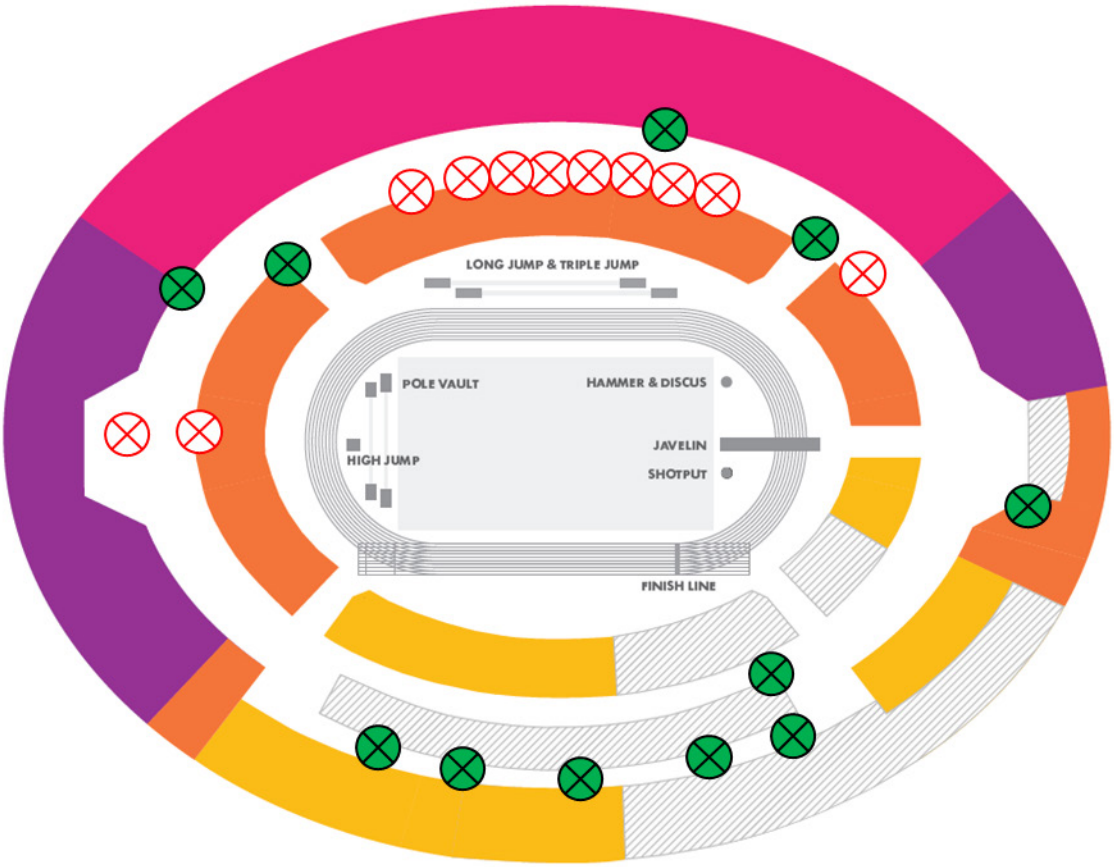

Figure 1. Camera layout within the stadium for the women's 400 m indicated by green in-filled circles.

A total of 20 cameras were employed to record the action during the 400 m semi-finals and finals. Five Sony RX10 M3 cameras operating at 100 Hz (shutter speed: 1/1250; ISO: 1600; FHD: 1920x1080 px) were positioned strategically along the home straight with their optical axes perpendicular to the running direction in order to capture motion in the sagittal plane and provide footage for the analysis of the split times. Five Sony PXW-FS7 cameras operating at 150 Hz (shutter speed: 1/1250; ISO: 1600; FHD: 1920x1080 px) were used to capture the motion of athletes as they were moving through the calibrated middle section. Each of the five Sony PXW-FS7 cameras was paired with an additional Sony RX10 M3 camera operating at 100 Hz as a precaution against the unlikely event of data capture loss. To provide footage for the analysis of the initial 300 m, five Canon EOS 700D cameras operating at 60 Hz (shutter speed: 1/1250; ISO: 1600; SHD: 1280x720 px) were used.

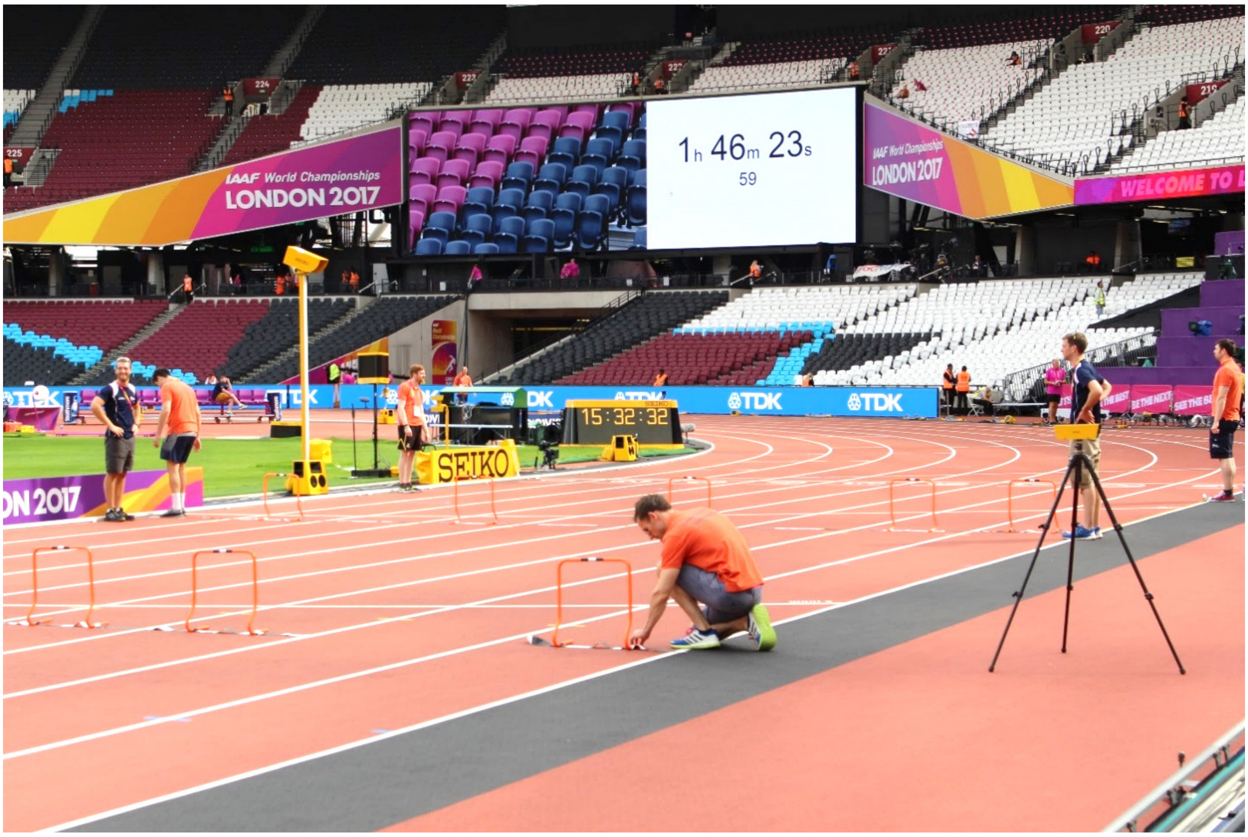

Figure 2. Set-up of the hurdle calibration system used to determine split intervals.

The video files were imported into SIMI Motion (SIMI Motion version 9.2.2, Simi Reality Motion Systems GmbH, Germany) and were manually digitised 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. Because of greater variability of performance across athletes during the middle calibration volume, compared to the shorter sprints, the digitising process centred upon critical events (e.g., touchdown and toe-off) rather than an analysis of the full sequence throughout the calibration volume. Each file was first digitised frame by frame and upon completion adjustments were made as necessary using the points over frame method. 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 sprint running stride 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.

Figure 3. The calibration frame was constructed and filmed before and after the competition.

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. Split times and kinematic characteristics were processed through SIMI Motion by using the 60, 100 and 150 Hz footage respectively. Where available, athletes' heights were obtained from 'Athletics 2017' (edited by Peter Matthews and published by the Association of Track and Field Statisticians), and online sources.

Figure 4. Action from the 400 m women's final.

Table 1. Variables selected to describe the performance of the athletes.

Variable	**Definition**
Positional analysis	Position of each athlete at each 100 m interval during the race. Also, throughout the home straight, the position at each 10 m interval (final), and for each 20 m interval (semi-finals).
Individual split times	Split time for each athlete based on the positional analysis above.
Mean speed	Mean speed for each athlete based on the individual split times.
Completed steps	Total recorded steps (e.g., right foot to left foot) during each 100 m interval.
Mean step length (split data)	Mean absolute length of each step during each 100 m interval and the relative value, based on an athlete's height, of each step during these intervals. The value of 1 relates to an athlete's height.
Step length	The distance covered from toe-off on one foot to toe-off on the other foot.
Relative step length	Step length as a proportion of the athlete's height (body height = 1.00).
Step rate	The number of steps per second (Hz).
Contact time	The time the foot is in contact with the ground.

Flight time	The time from toe-off (TO) of one foot to touchdown (TD) of the other foot.
Step time	Contact time + flight time.
Step velocity	Step length divided by step time.
Swing time	The time that the foot is not in contact with the ground during one full stride.
DCM TD	The horizontal distance between the ground contact point (foot tip) at TD and the CM.
DCM TO	The horizontal distance between the ground contact point (foot tip) at TO and the CM.
Trunk angle (α)	The angle of the trunk relative to the horizontal and considered to be 90° in the upright position.
Knee angle (β)	The angle between the thigh and lower leg and considered to be 180° in the anatomical standing position.
Contact leg hip angle (γ)	The shoulder-hip-knee angle of the contact side.
Swing leg hip angle (δ)	The shoulder-hip-knee angle of the swing side. ***Note:*** *angle taken at toe-off only.*
Contact thigh angle (ε)	The angle between the thigh of the contact leg and the vertical.
Swing thigh angle (ζ)	The angle between the thigh of the swing leg and the vertical.
Thigh separation angle (η)	The angle between the thighs of the contact and swing legs. This has been calculated as the difference between ε and ζ.
Shank angle (θ)	The angle of the lower leg relative to the running surface and considered to be 90° when the shank is perpendicular to the running surface.
Ankle angle (ι)	The angle between the lower leg and the foot and considered to be 90° in the anatomical standing position.

Note: *CM = Centre of mass.*

RESULTS – Final

Performance data

The tables below display the season's (SB) and personal best (PB) times of each athlete competing in the final before the World Championships, and their performance during the semi-finals (Table 2). These values are then compared to their performance in the final itself (Table 3).

Table 2. Individual season's (SB) and personal bests (PB), and performance during the semi-final (SF).

Athlete	SB	*rank*	PB	*rank*	SF	*rank*	*notes*
FRANCIS	49.96 s	*3*	49.94 s	*6*	50.37 s	4	
NASER	50.57 s	*6*	50.57 s	*8*	50.08 s	1	*NR*
FELIX	49.65 s	*1*	49.26 s	*1*	50.12 s	2	
MILLER-UIBO	49.77 s	*2*	49.44 s	*2*	50.36 s	3	
JACKSON	50.05 s	*4*	49.83 s	*4*	50.70 s	8	
McPHERSON	50.68 s	*7*	49.92 s	*5*	50.56 s	5	*SB*
MUPOPO	51.09 s	*8*	50.22 s	*7*	50.60 s	6	*SB*
WILLIAMS-MILLS	50.14 s	*5*	49.63 s	*3*	50.67 s	7	

Key: *SB = season's best, PB = personal best, SF = semi-final, NR = national record.*

Table 3. Comparison of athletes' performance during the final compared to PB, SB and semi-finals (SF).

Athlete	FINAL	*notes*	vs. SF	vs. SB	vs. PB
FRANCIS	49.92 s	*PB*	–0.45 s	–0.02 s	–0.04 s
NASER	50.06 s	*NR*	–0.02 s	–0.51 s	–0.51 s
FELIX	50.08 s		–0.04 s	0.82 s	0.43 s
MILLER-UIBO	50.49 s		0.13 s	1.05 s	0.72 s
JACKSON	50.76 s		0.06 s	0.93 s	0.71 s
McPHERSON	50.86 s		0.3 s	0.94 s	0.18 s
MUPOPO	51.15 s		0.55 s	0.93 s	0.06 s
WILLIAMS-MILLS	51.48 s		0.81 s	1.85 s	1.34 s

Key: *SB = season's best, PB = personal best, SF = semi-final.*

Positional analysis

Figure 5 shows the relative position of each athlete at each 100 m split throughout the race. A more detailed overview of the relative positions at each 10 m split throughout the home straight is presented in Figure 6.

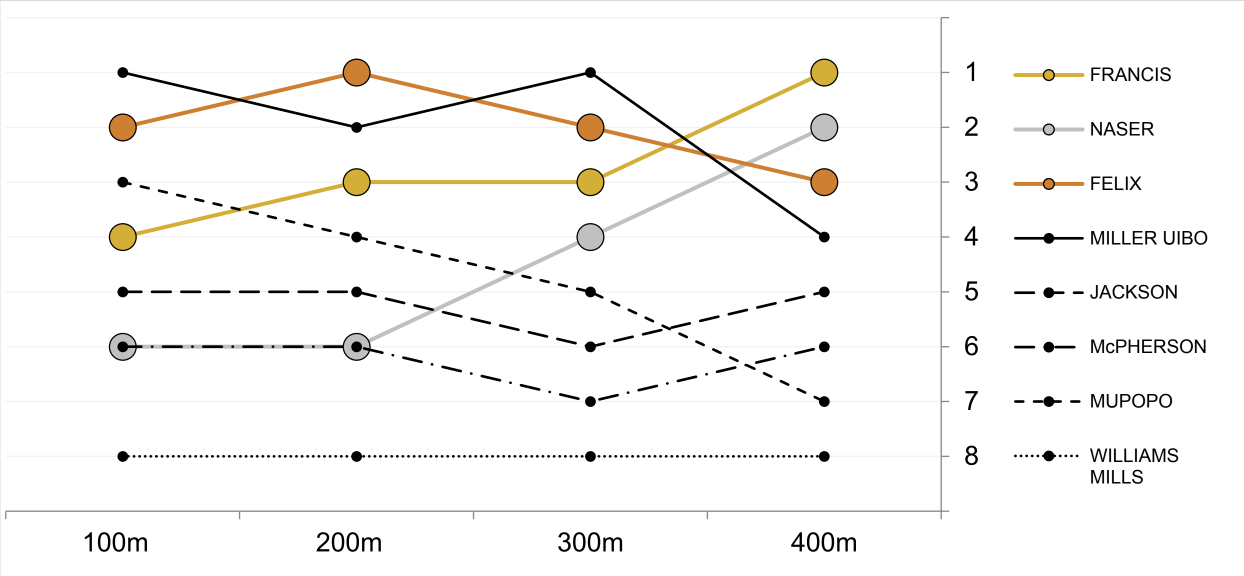

Figure 5. Positions at the end of each 100 m split.

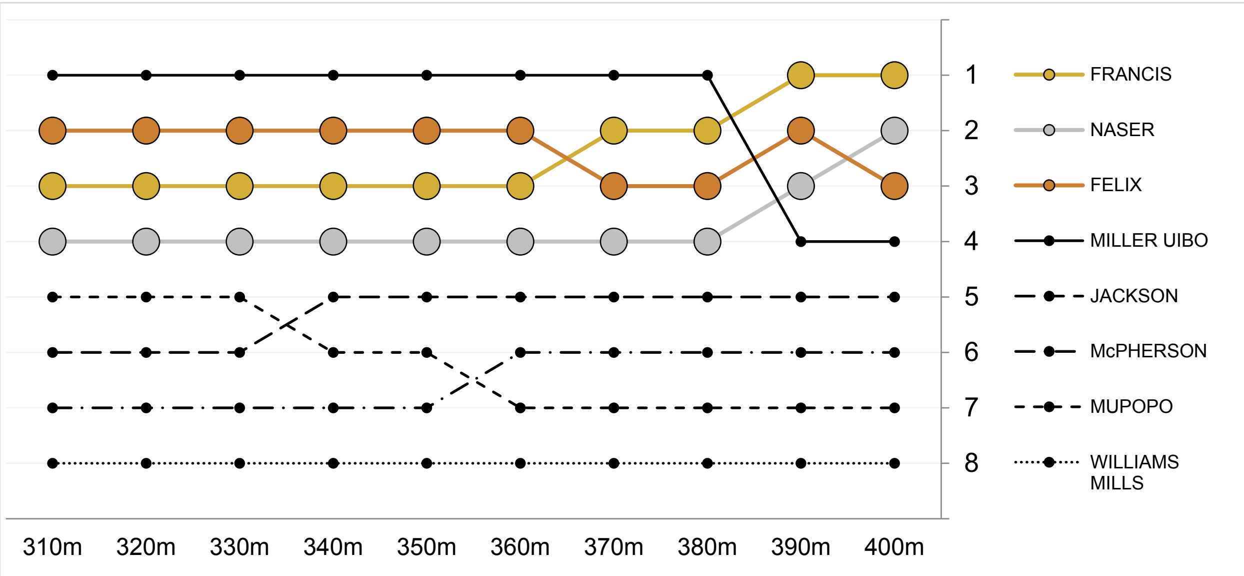

Figure 6. Positions at the end of each 10 m split throughout the home straight.

Individual split times

The following graphs display the split times of all athletes over each: 200 m split (Figures 7 and 8), consecutive 100 m splits (Figure 9; note: 0-100 m is displayed without the reaction time) and consecutive 10 m splits throughout the home straight (Figures 9 and 10). The mean speed over consecutive 10 m splits throughout the home straight is presented in Figure 11. Please note that split times have been rounded mathematically to two decimal places throughout this report. However, the official result is always rounded up in accordance with the IAAF Competition Rules – this causes some instances where our total race times differ by 0.01 seconds. Any instances of this are highlighted in the notes section of the performance tables by an asterisk (*).

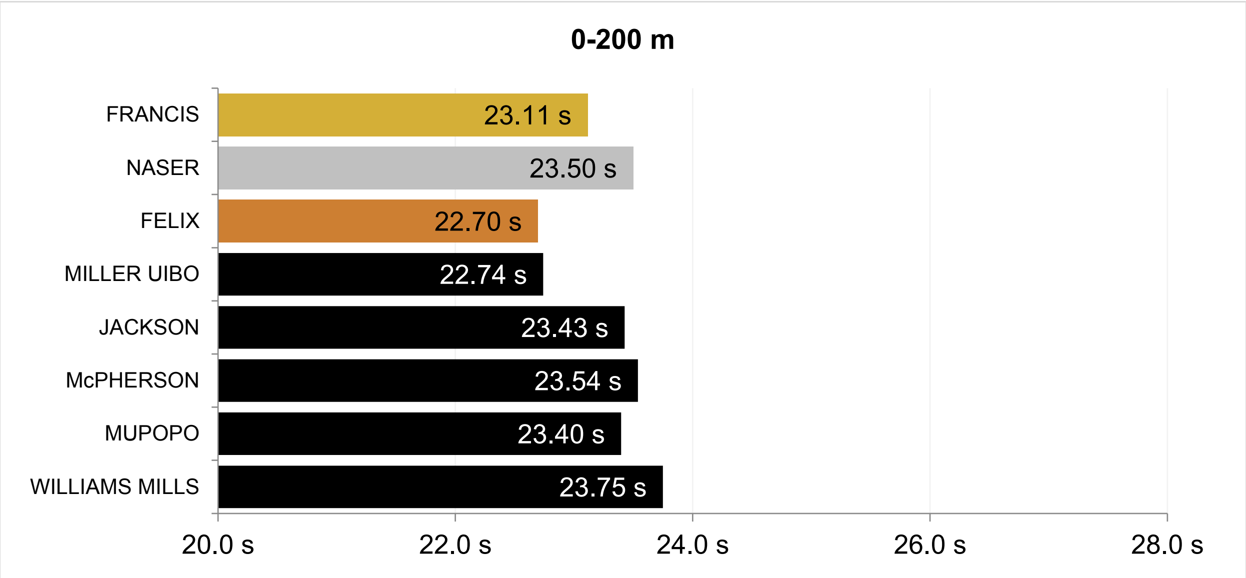

Figure 7. Individual 0-200 m split times (minus reaction time).

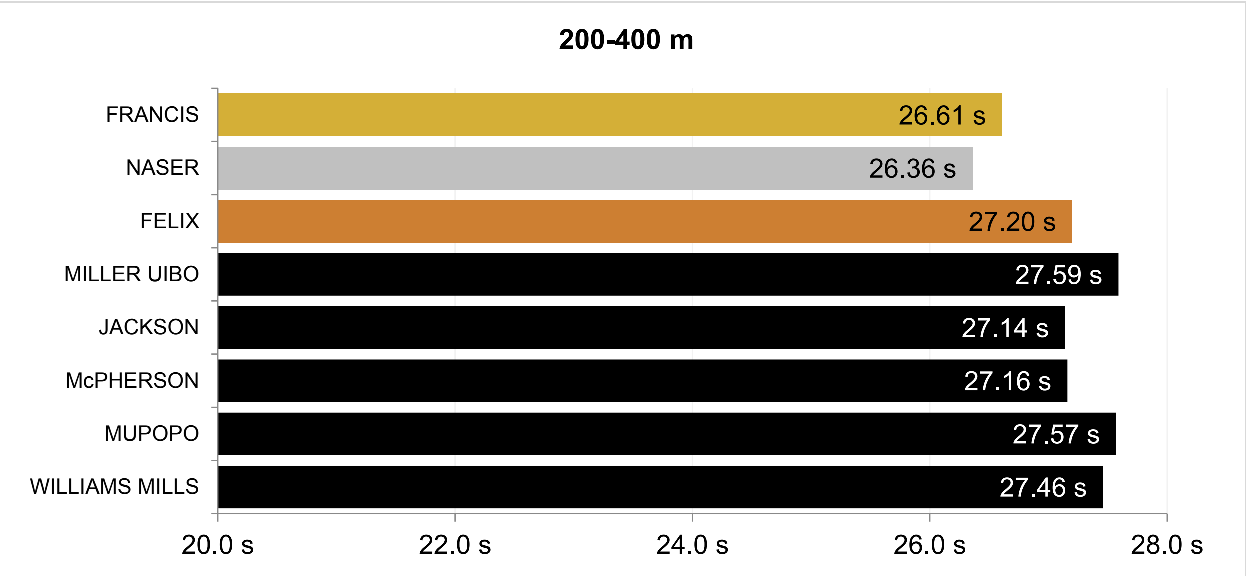

Figure 8. Individual 200-400 m split times.

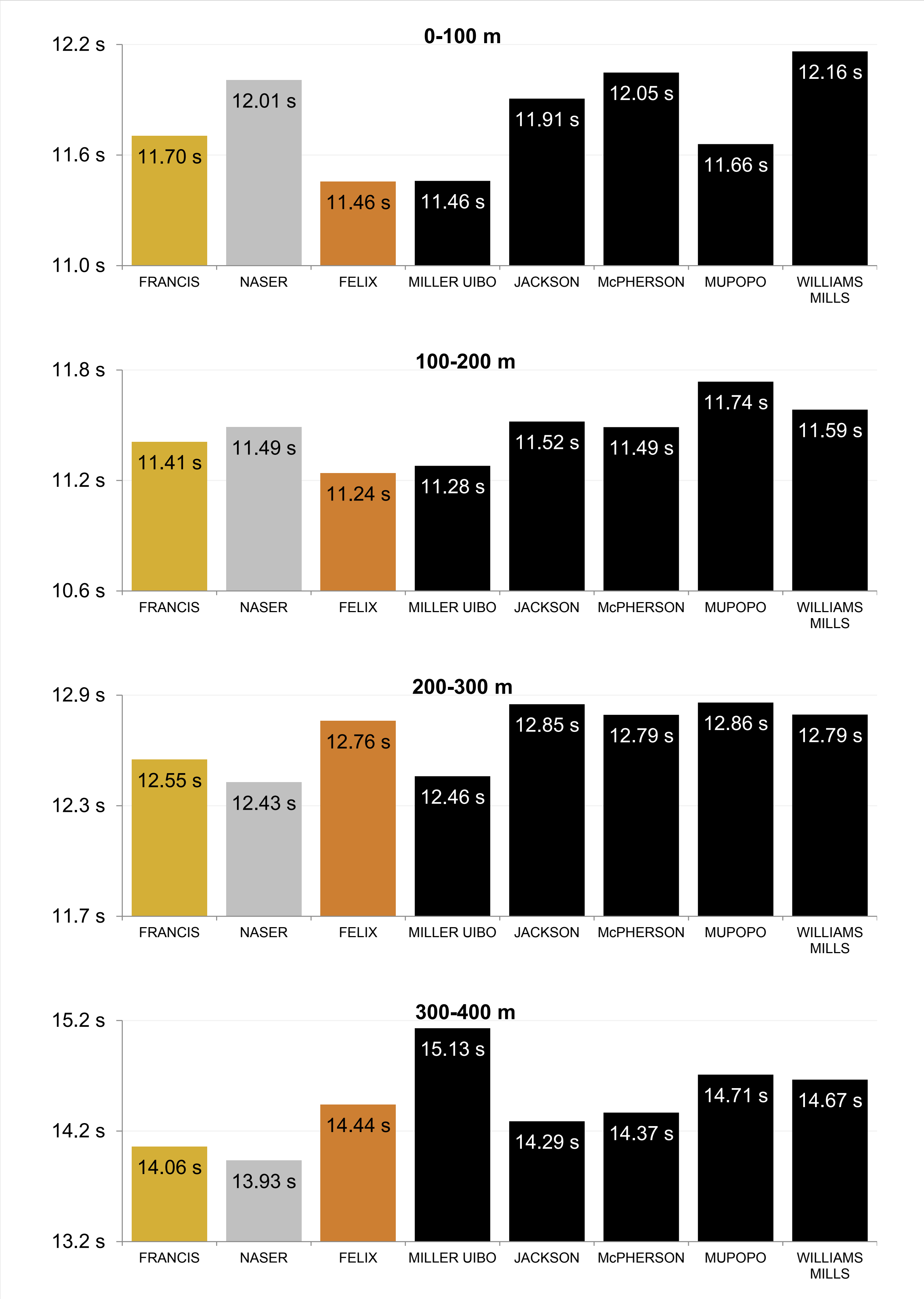

Figure 9. Individual consecutive 100 m split times (0-100 m minus reaction time).

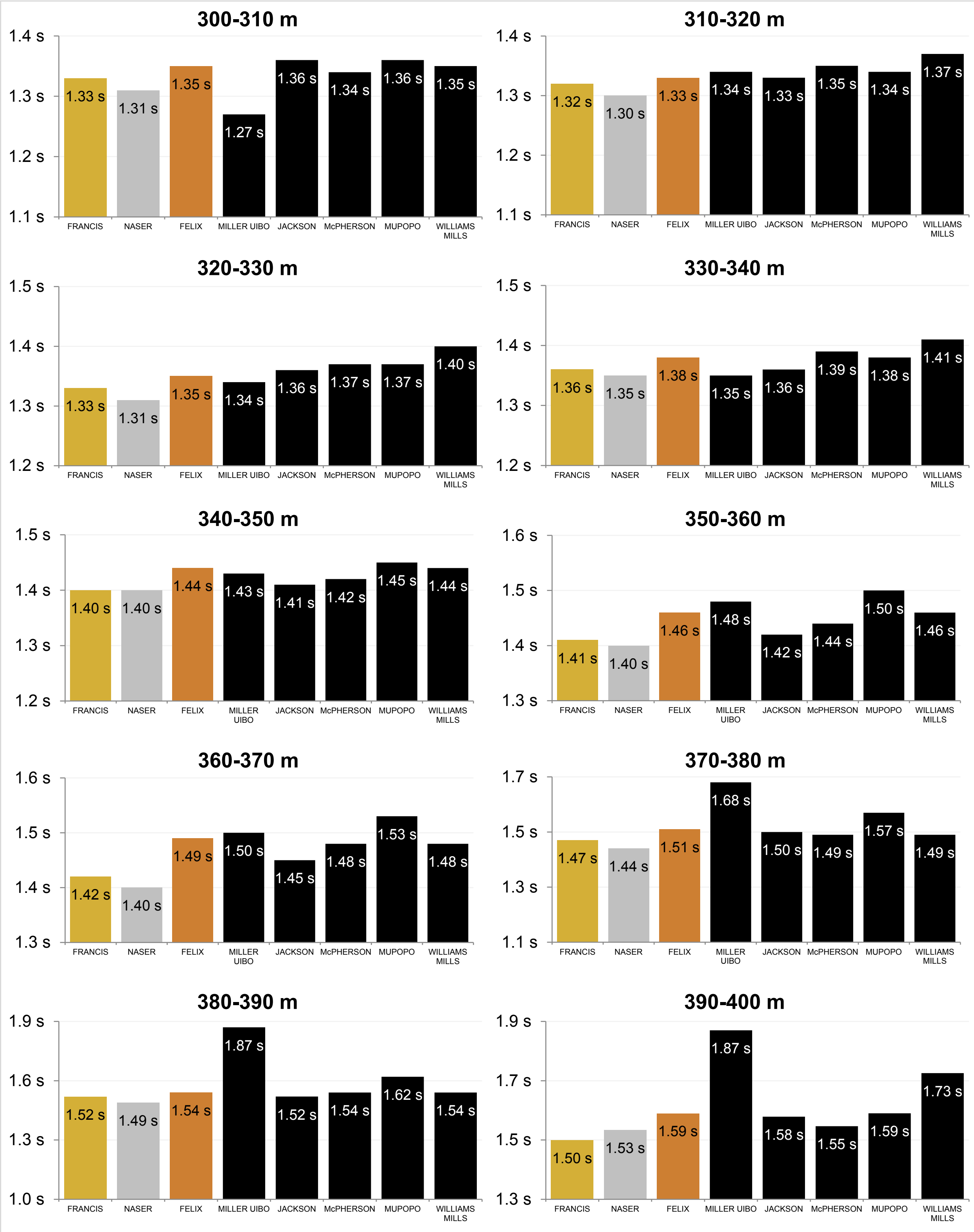

Figure 10. Individual consecutive 10 m split times throughout the home straight.

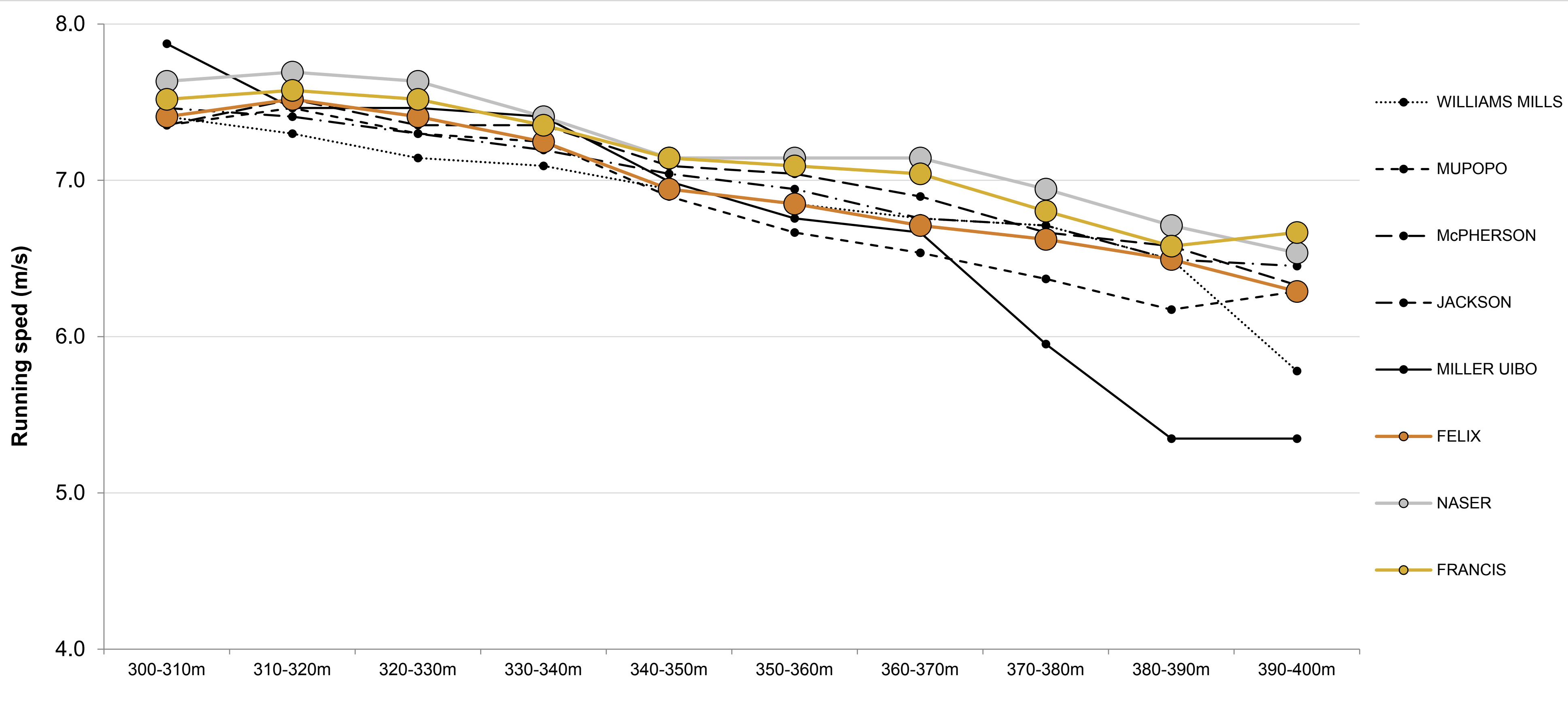

Figure 11. Mean running speed during each 10 m split throughout the home straight.

Completed steps and step length

The following graphs show step information of individual athletes over progressive 100 m splits for the mean step length and relative to each athlete's stature (Figure 12). The total completed steps for the race and during each 100 m split for each athlete is presented in Figure 13.

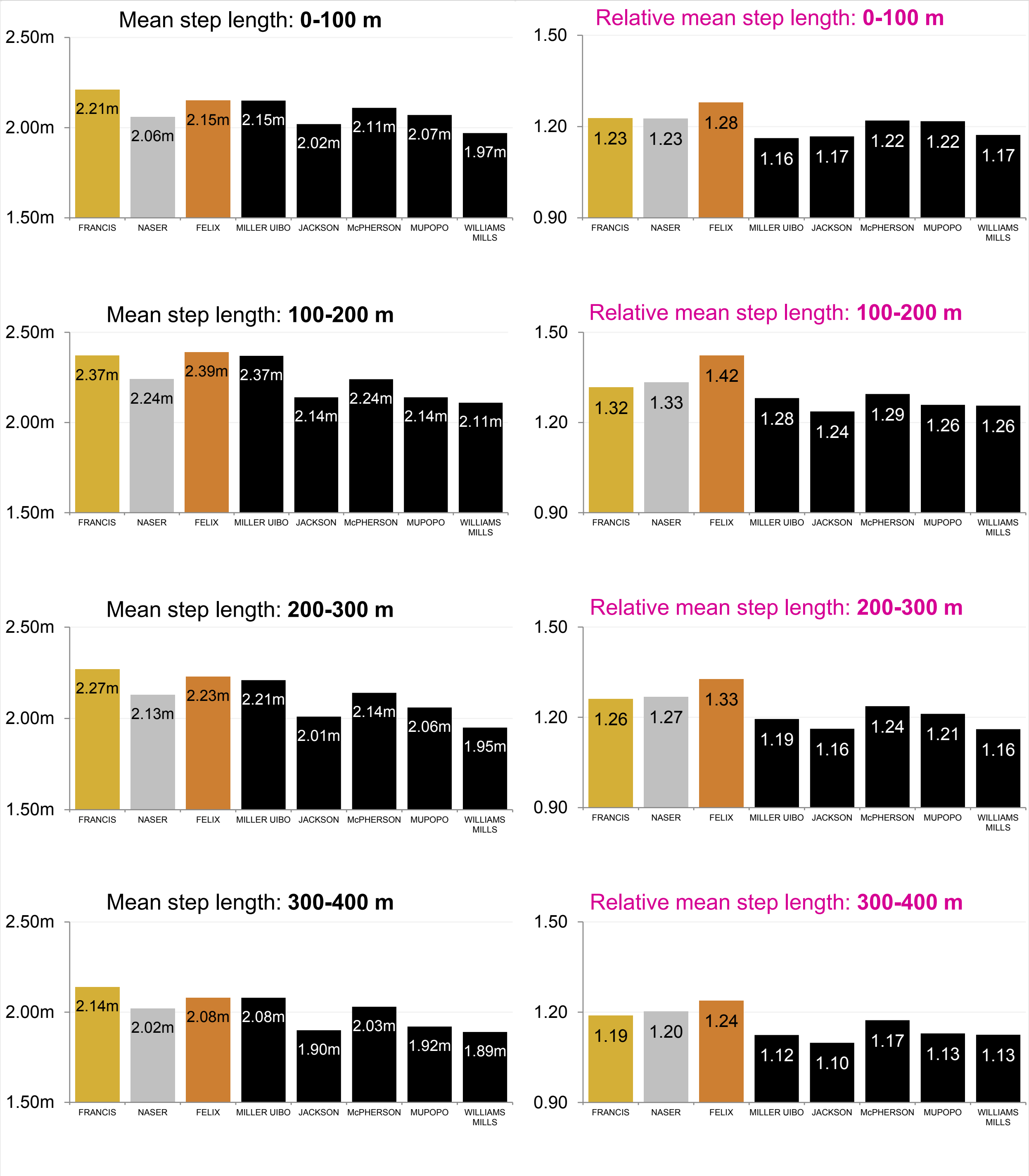

Figure 12. Mean and relative (height) step length during each 100 m split.

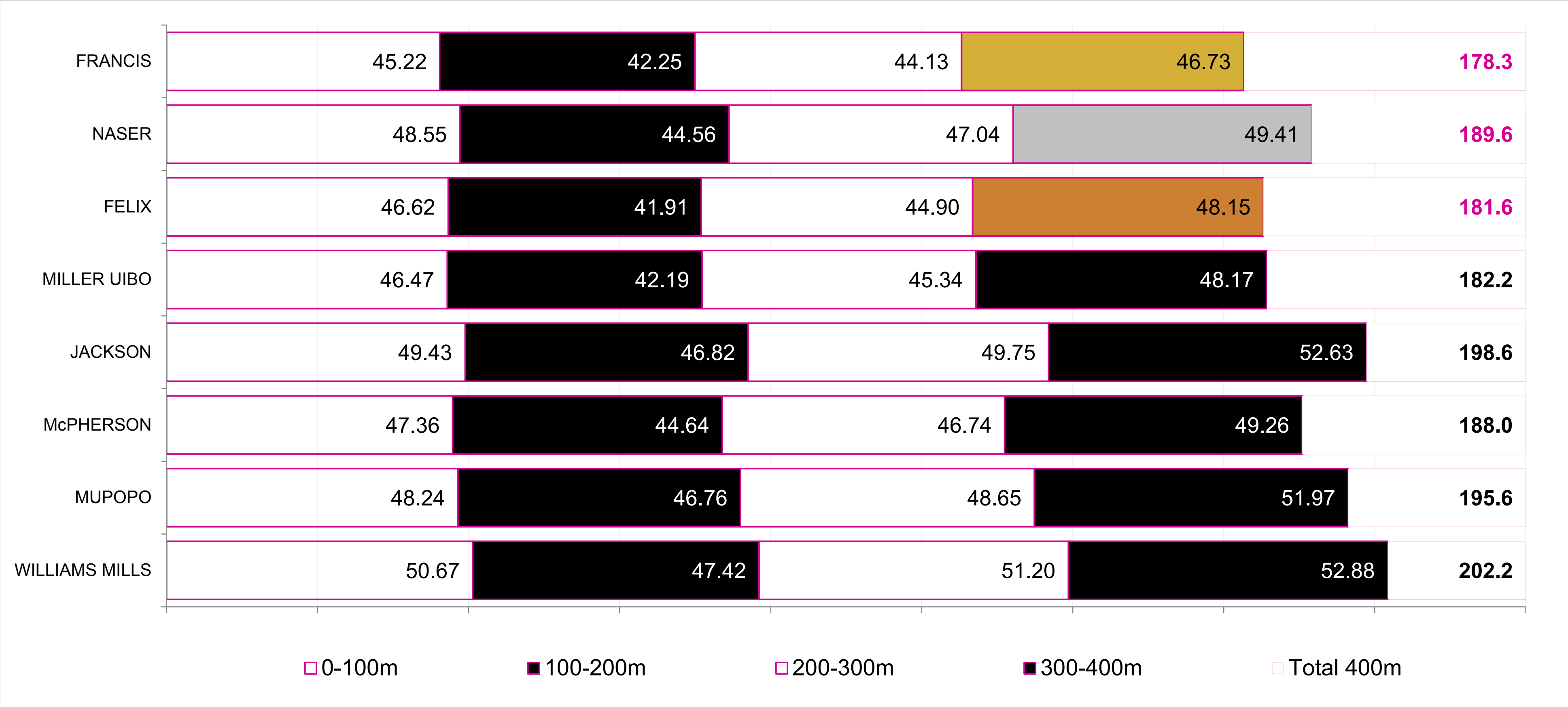

Figure 13. Total completed steps during the race and throughout each consecutive 100 m split.

GOLD MEDALLIST: Phyllis Francis

	RT	100 m	200 m	300 m	RESULT
Final	0.196 s	11.90 s	23.31 s	35.86 s	**49.92 s**
Rank	*6th*	*4th*	*3rd*	*3rd*	***1st***
vs. silver	–0.007 s	–0.31 s	–0.39 s	–0.27 s	–0.14 s
vs. bronze	+0.012 s	+0.26 s	+0.43 s	+0.22 s	–0.16 s
Semi-Final	0.187 s	12.09 s	23.38 s	36.15 s	**50.37 s**
Rank	*8th*	*=3rd*	*1st*	*2nd*	***4th***

	0-100 m	100-200 m	0-200 m	200-300 m	300-400 m	200-400 m
Final	11.70 s	11.41 s	23.11 s	12.55 s	14.06 s	26.61 s
Rank	*4th*	*3rd*	*3rd*	*3rd*	*2nd*	*2nd*
vs. silver	–0.30 s	–0.08 s	–0.38 s	+0.12 s	+0.13 s	–0.25 s
vs. bronze	+0.25 s	+0.17 s	+0.42 s	–0.21 s	–0.38 s	–0.59 s
Semi-Final	11.91 s	11.28 s	23.19 s	12.77 s	14.22 s	26.99 s
Rank	*4th*	*1st*	*1st*	*8th*	*13th*	*13th*

Kinematic characteristics

This section presents the results from the digitised data within the calibration zone (i.e., around 350 m) along the home straight. All variables have been described previously (Table 1).

Table 4. Mean step rate, step velocity and step length for each finalist around 350 m.

	Step velocity (m/s)	Step rate (Hz)	Step length (m)	#*relative*
FRANCIS	7.32	3.37	2.17	1.21
NASER	7.36	3.62	2.03	1.21
FELIX	6.90	3.33	2.07	1.23
MILLER-UIBO	7.12	3.29	2.16	1.17
JACKSON	7.02	3.80	1.85	1.07
McPHERSON	6.99	3.44	2.03	1.17
MUPOPO	6.91	3.58	1.93	1.14
WILLIAMS-MILLS	7.05	3.75	1.88	1.12

Note: *Step velocity calculated from step length and step time; # relative step length based on athlete's height.*

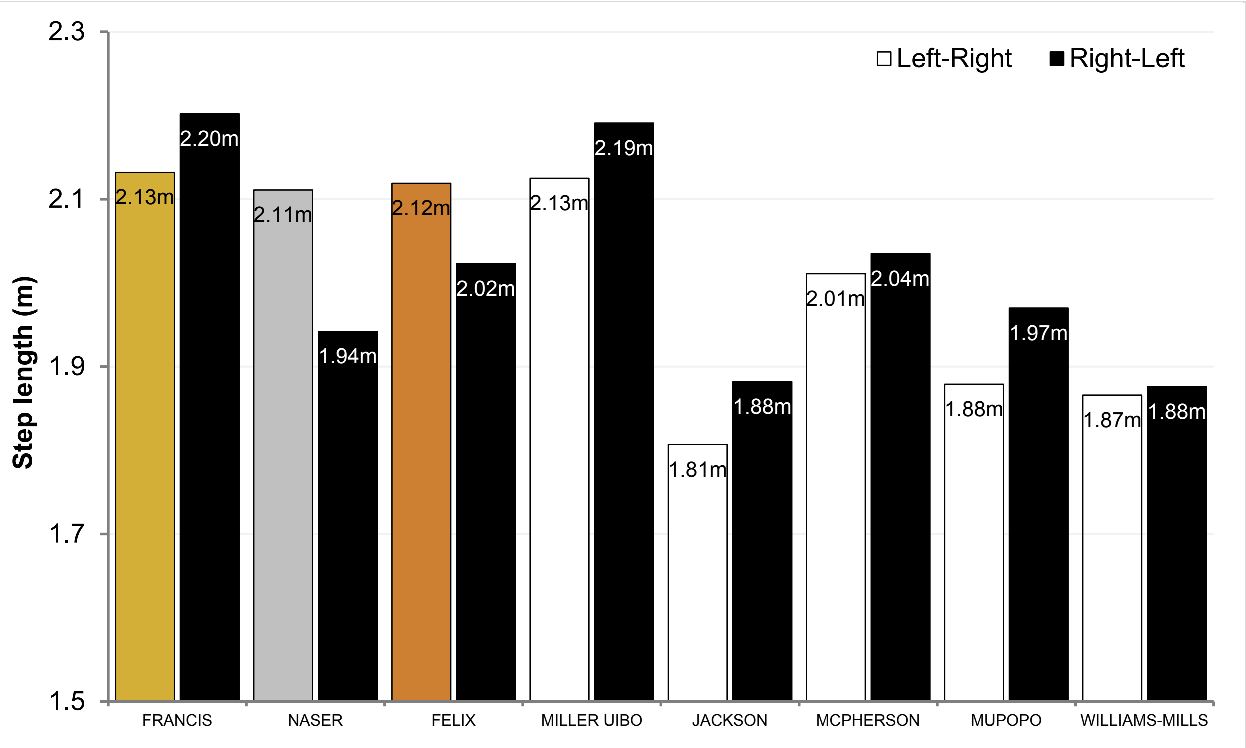

Figure 14. Step lengths for each of the finalists around 350 m.

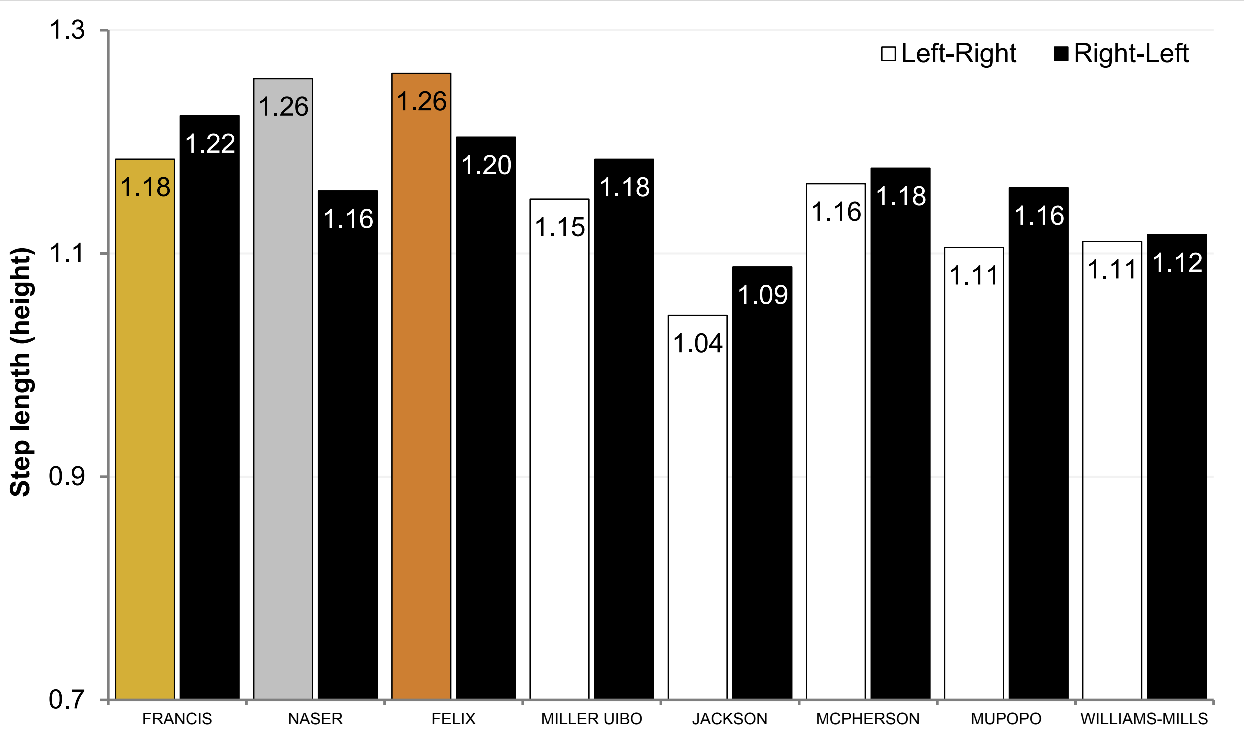

Figure 15. Relative (height) step lengths for each of the finalists around 350 m.

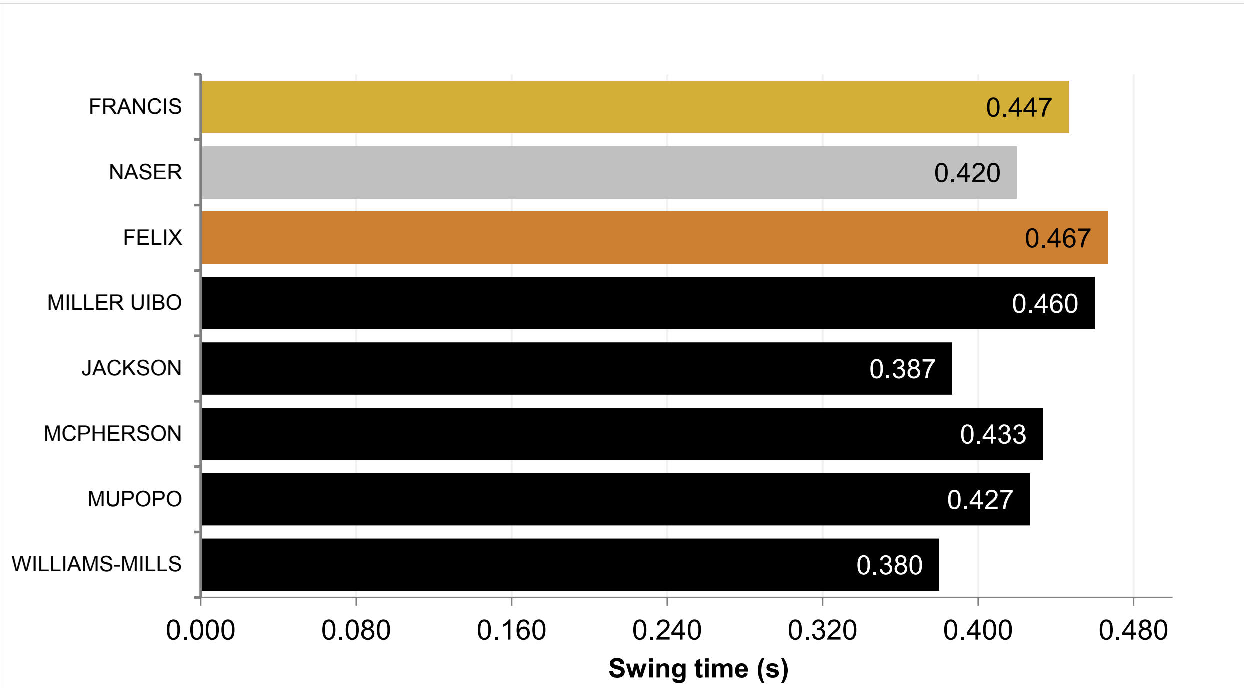

Figure 16. Swing times for each of the finalists around 350 m.

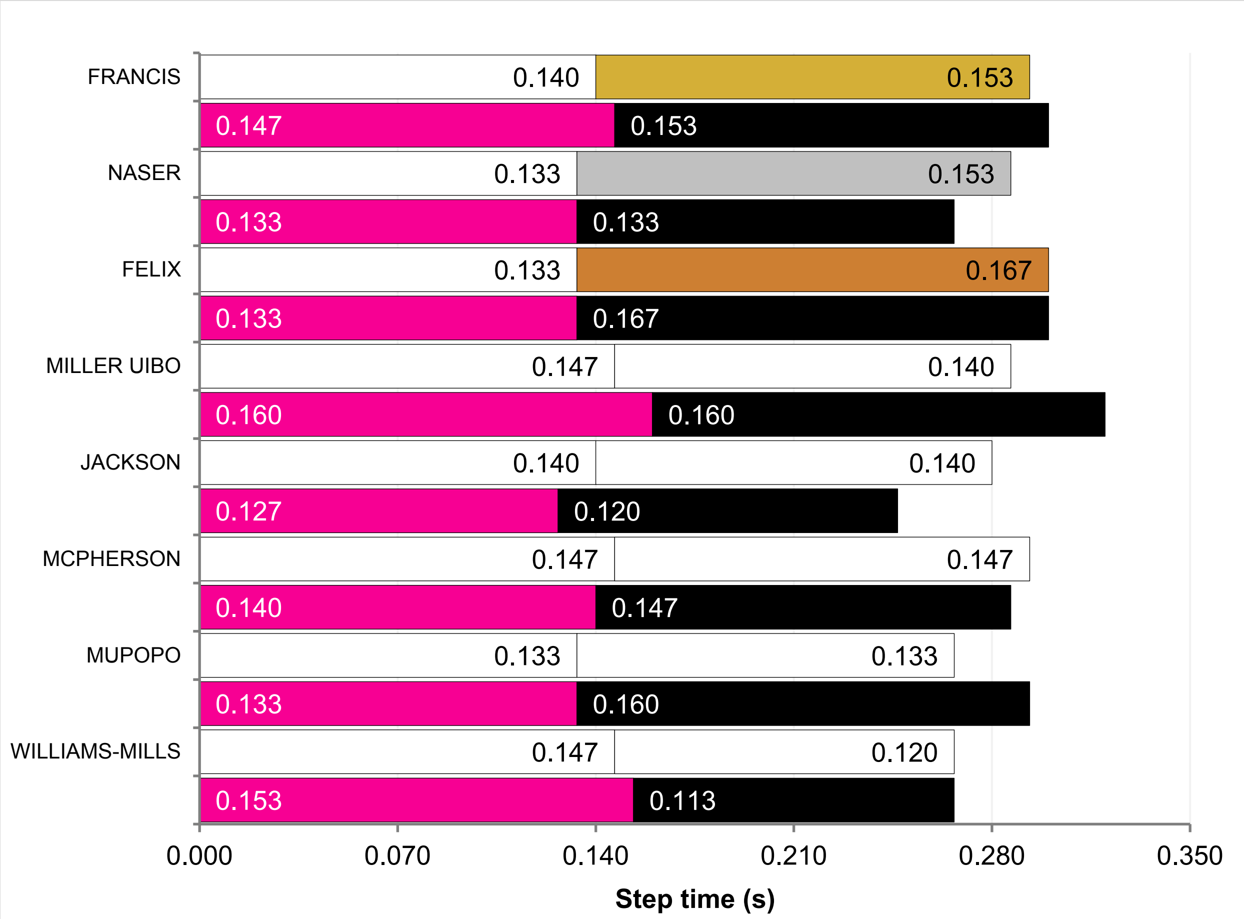

Figure 17. Individual contact and flight times for each of the finalists around 350 m. For each athlete, the top column (black text) represents the left foot contact and left-to-right flight time, and the bottom column (white text) represents the right foot contact (pink shading) and right-to-left flight time (black shading).

Table 5. Horizontal distance to the centre of mass (DCM) at touchdown (TD) and toe-off (TO).

	DCM TD (m / % body height)		DCM TO (m / % body height)	
	Left	Right	Left	Right
FRANCIS	0.48 / 27	0.48 / 27	0.50 / 28	0.57 / 32
NASER	0.52 / 31	0.52 / 31	0.39 / 23	0.43 / 26
FELIX	0.41 / 24	0.43 / 25	0.50 / 30	0.45 / 27
MILLER UIBO	0.45 / 25	0.51 / 28	0.58 / 31	0.56 / 30
JACKSON	0.48 / 28	0.43 / 25	0.30 / 17	0.49 / 28
MCPHERSON	0.44 / 25	0.42 / 24	0.52 / 30	0.51 / 30
MUPOPO	0.43 / 25	0.46 / 27	0.44 / 26	0.39 / 23
WILLIAMS-MILLS	0.45 / 27	0.43 / 26	0.55 / 33	0.59 / 35

Note: *Data displayed as an absolute distance and as a percentage of the athletes' heights. Percentage values have been rounded to the nearest integer.*

Angular kinematics

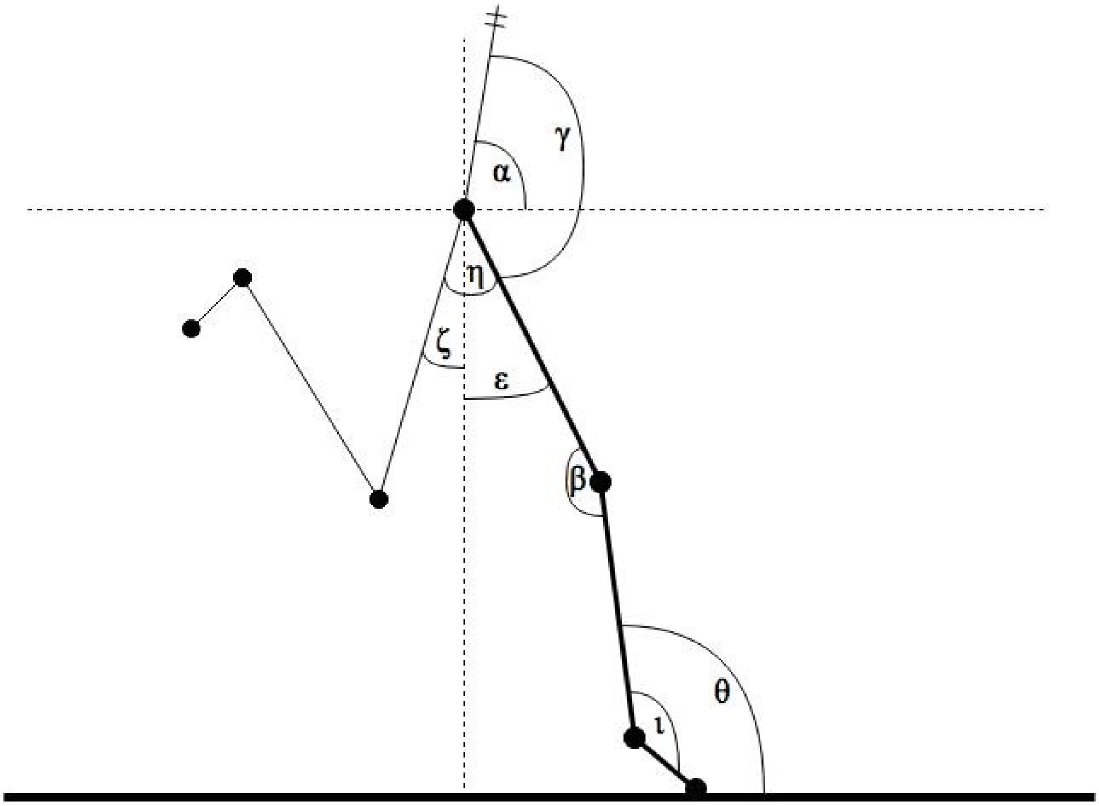

Figure 18. Body schematic denoting joint angles measured at touchdown. This does not represent any athlete's posture but is merely for illustration purposes.

Table 6. Joint angles at touchdown for the medallists.

	FRANCIS		NASER		FELIX	
	Left (°)	Right (°)	Left (°)	Right (°)	Left (°)	Right (°)
α	84.0	86.1	87.1	88.5	83.2	84.0
β	158.0	148.9	149.0	154.5	157.7	151.3
γ	149.2	153.1	149.8	158.2	153.5	154.3
ε	30.5	31.0	33.7	30.6	24.8	28.2
ζ	–7.5	–5.9	1.2	1.0	–0.4	–8.5
η	–38.0	–36.9	–32.5	–29.6	–25.2	–36.7
θ	101.9	97.5	94.2	95.8	101.0	99.1
ι	125.8	109.6	116.0	118.9	117.7	106.0

Note: *For angles* **ε** *and* **ζ***, a positive value indicates that the thigh segment was in front of the vertical axis. For angle* **η***, a negative value indicates that the swing leg is behind the touchdown leg at the point of contact, whereas a positive value indicates the swing thigh is in front of the contralateral thigh segment. The 2-D schematic should not be used as a model to combine angles as different landmarks have been used for defining certain angles.*

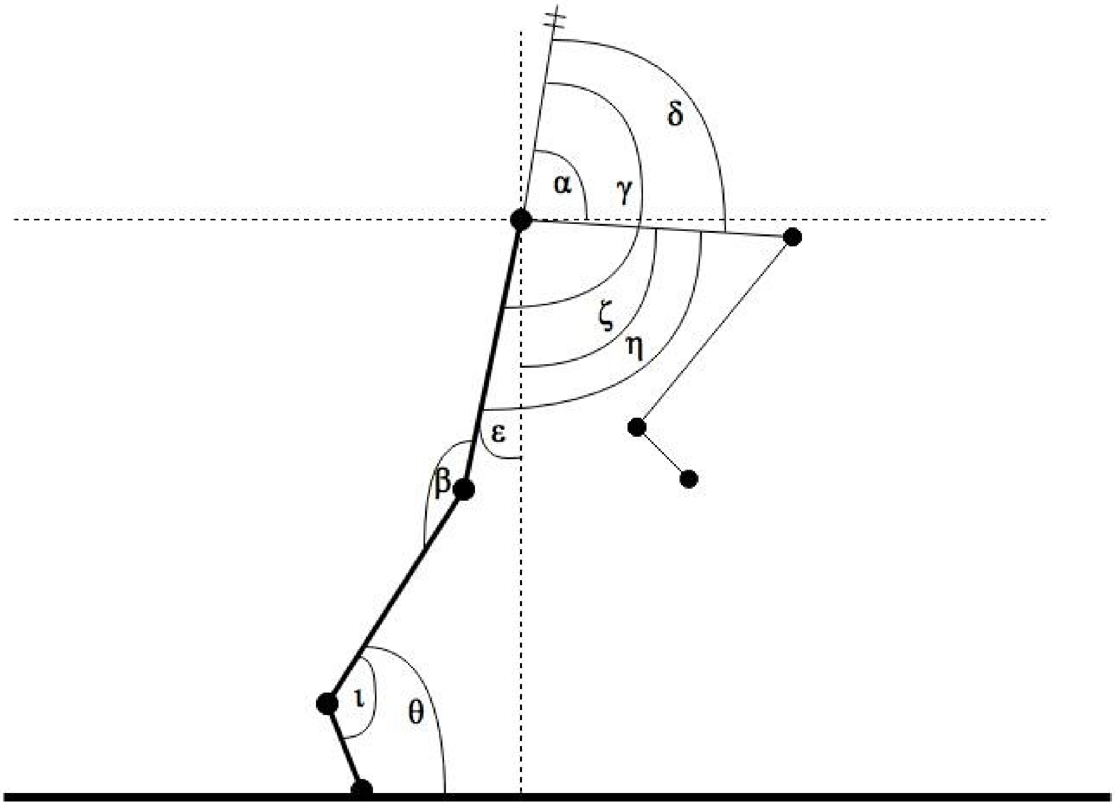

Figure 19. Body schematic denoting joint angles measured at toe-off. This does not represent any athlete's posture but is merely for illustration purposes.

Table 7. Joint angles at toe-off for the medallists.

	FRANCIS		NASER		FELIX	
	Left (°)	Right (°)	Left (°)	Right (°)	Left (°)	Right (°)
α	87.4	87.3	84.9	86.3	83.4	88.2
β	169.2	162.8	167.0	163.3	166.8	167.7
γ	202.3	202.8	196.3	207.2	196.3	203.9
δ	129.0	134.5	119.3	133.2	117.9	130.2
ε	–27.9	–28.3	–30.0	–28.5	–28.5	–29.1
ζ	54.6	55.8	65.6	57.1	61.1	54.8
η	82.5	84.1	95.6	85.6	89.6	83.9
θ	51.1	45.1	47.1	45.3	48.5	49.5
ι	140.9	147.9	142.7	141.2	139.3	122.0

Note: *For angles* **ε** *and* ζ*, a positive value indicates that the thigh segment was in front of the vertical axis. For angle* **η***, a negative value indicates that the swing leg is behind the touchdown leg at the point of contact, whereas a positive value indicates the s wing thigh is in front of the contralateral thigh segment. The 2-D schematic should not be used as a model to combine angles as different landmarks have been used for defining certain angles.*

Table 8. Joint angles at touchdown for the remaining five finalists.

	MILLER-UIBO		JACKSON		McPHERSON		MUPOPO		WILLIAMS-MILLS	
	Left (°)	Right (°)	Left (°)	Right (°)	Left (°)	Right (°)	Left (°)	Right (°)	Left (°)	Right (°)
α	81.7	84.7	88.7	83.9	85.9	83.4	85.7	87.5	88.3	83.9
β	158.5	144.8	169.1	164.9	153.6	144.0	155.3	147.3	166.7	158.8
γ	151.4	145.7	165.5	156.1	151.0	151.1	161.3	157.0	162.4	150.5
ε	26.4	34.3	22.3	28.0	32.0	32.6	24.6	31.0	20.8	26.6
ζ	2.6	–6.9	–4.0	3.3	–12.7	–4.9	–1.9	–10.4	–8.6	–7.0
η	–23.8	–41.2	–26.3	–24.7	–44.7	–37.5	–26.5	–41.4	–29.4	–33.6
θ	97.9	94.7	103.7	93.3	99.3	94.5	101.9	98.0	104.5	98.2
ι	109.3	100.9	117.4	108.7	114.1	99.8	110.8	101.8	116.9	111.1

Note: *For angles* **ε** *and* **ζ**, *a positive value indicates that the thigh segment was in front of the vertical axis. For angle* **η**, *a negative value indicates that the swing leg is behind the touchdown leg at the point of contact, whereas a positive value indicates the swing thigh is in front of the contralateral thigh segment. The 2-D schematic should not be used as a model to combine angles as different landmarks have been used for defining certain angles.*

Table 9. Joint angles at toe-off for the remaining five finalists.

	MILLER-UIBO		JACKSON		McPHERSON		MUPOPO		WILLIAMS-MILLS	
	Left (°)	Right (°)	Left (°)	Right (°)	Left (°)	Right (°)	Left (°)	Right (°)	Left (°)	Right (°)
α	84.8	89.0	88.1	86.0	89.6	83.9	84.4	85.5	89.4	85.0
β	167.0	171.6	174.5	160.6	161.2	166.6	160.3	157.7	173.7	163.2
γ	202.7	208.0	209.8	204.7	201.3	204.2	205.0	200.9	211.5	200.6
δ	126.3	129.4	135.4	139.3	136.9	129.2	139.6	132.1	126.2	120.9
ε	–30.0	–32.7	–33.7	–23.5	–28.4	–30.6	–26.0	–19.2	–36.9	–31.0
ζ	56.8	56.9	52.3	47.4	49.4	53.9	50.9	51.4	57.9	61.5
η	86.8	89.6	86.0	70.9	77.8	84.5	76.9	70.6	94.8	92.5
θ	47.8	49.3	52.2	47.4	43.0	46.1	44.3	48.5	46.6	42.7
ι	144.9	139.2	94.5	141.1	132.6	135.5	126.0	125.6	144.0	141.9

Note: *For angles* **ε** *and* **ζ**, *a positive value indicates that the thigh segment was in front of the vertical axis. For angle* **η**, *a negative value indicates that the swing leg is behind the touchdown leg at the point of contact, whereas a positive value indicates the swing thigh is in front of the contralateral thigh segment. The 2-D schematic should not be used as a model to combine angles as different landmarks have been used for defining certain angles.*

RESULTS – Semi-Final 1

Performance data

Table 10 below displays the ranking of each athlete before the World Championships across all athletes qualifying for the semi-finals, based on their season's (SB) and personal best (PB) times, and a comparison to their semi-final time.

Table 10. Athletes' ranking based on SB and PB, and comparison to their semi-final performance.

Athlete	*SB rank*	*PB rank*	SEMI-FINAL	*notes*	vs. SB	vs. PB
MILLER-UIBO	*3*	*3*	50.36 s	*Q*	0.59 s	0.92 s
McPHERSON	*10*	*7*	50.56 s	*Q SB*	–0.12 s	0.64 s
HAYES	*2*	*5*	50.71 s		0.99 s	0.99 s
L-ČUDARE	*15*	*18*	51.57 s		0.20 s	0.20 s
GÓMEZ	*17*	*20*	52.01 s		0.55 s	0.55 s
RAZOR	*19*	*12*	52.09 s		0.47 s	1.72 s
GEORGE	*11*	*14*	52.60 s		1.54 s	1.89 s
KELLY	*20*	*21*	54.50 s		2.87 s	2.87 s

Key: *Q = automatic qualifier, q = secondary qualifier, SB = season's best, PB = personal best, NR = national record.*

Positional analysis

Figure 20 shows the relative position of each athlete at each 100 m split throughout the race.

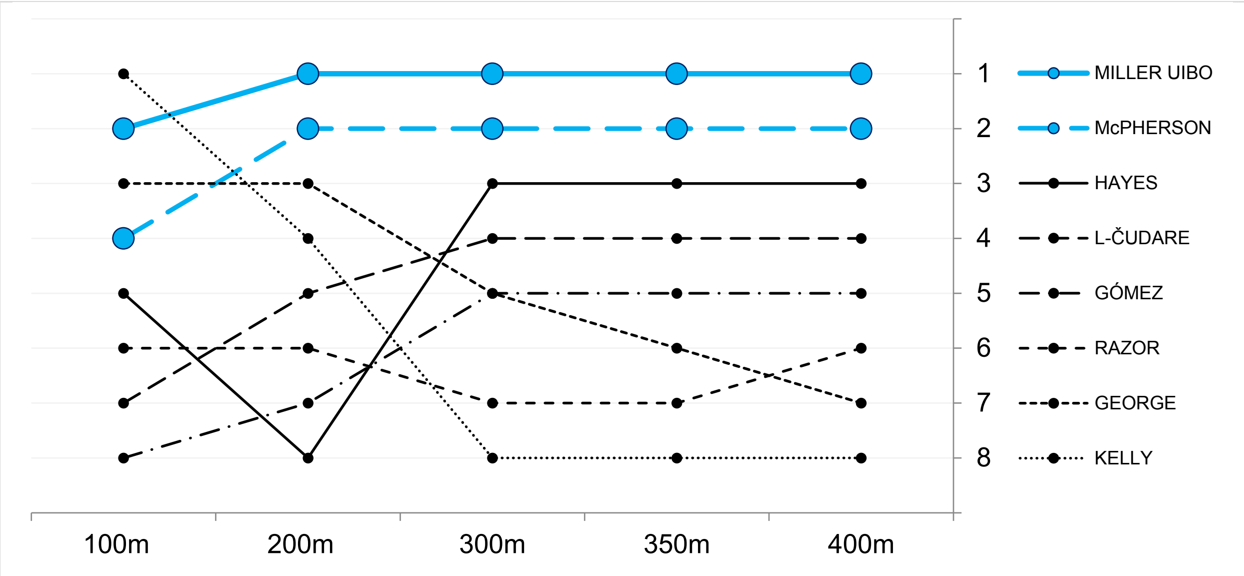

Figure 20. Positions at the end of each 100 m split.

Individual split times

The following graphs display the split times of all athletes over each: 200 m split (Figures 21 and 22), consecutive 100 m splits (note: 0-100 m is displayed without the reaction time) including consecutive 50 m splits during the home straight (Figure 23). The mean speeds over progressive 100 m (from 0-300 metres) and 50 metre (from 300-400 metres) splits are presented in Figure 24.

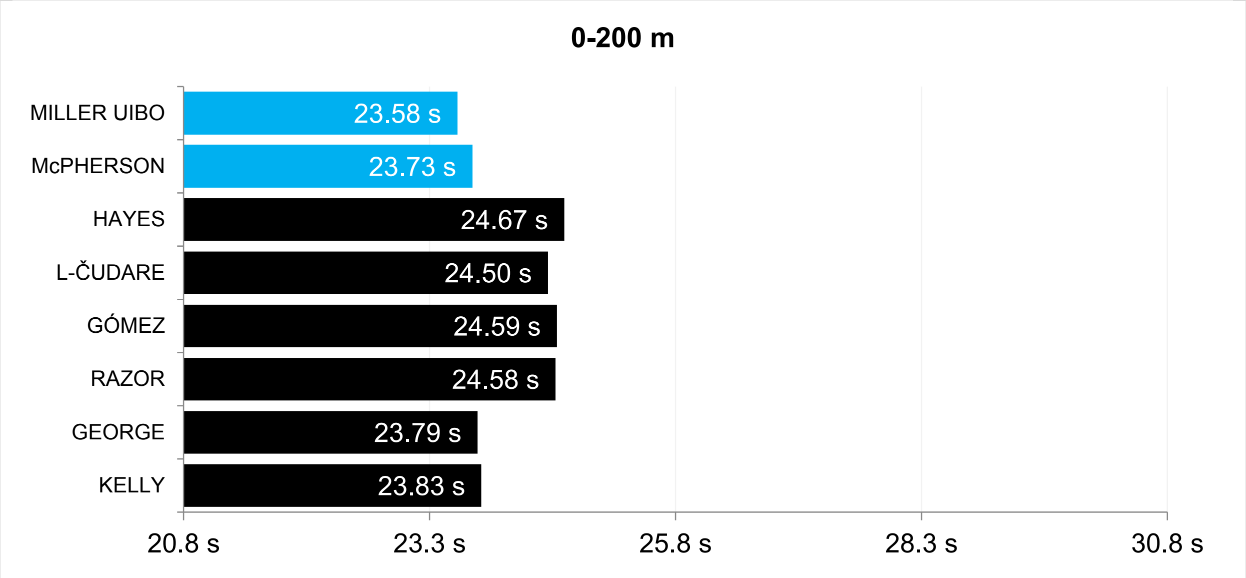

Figure 21. Individual 0-200 m split times (minus reaction time).

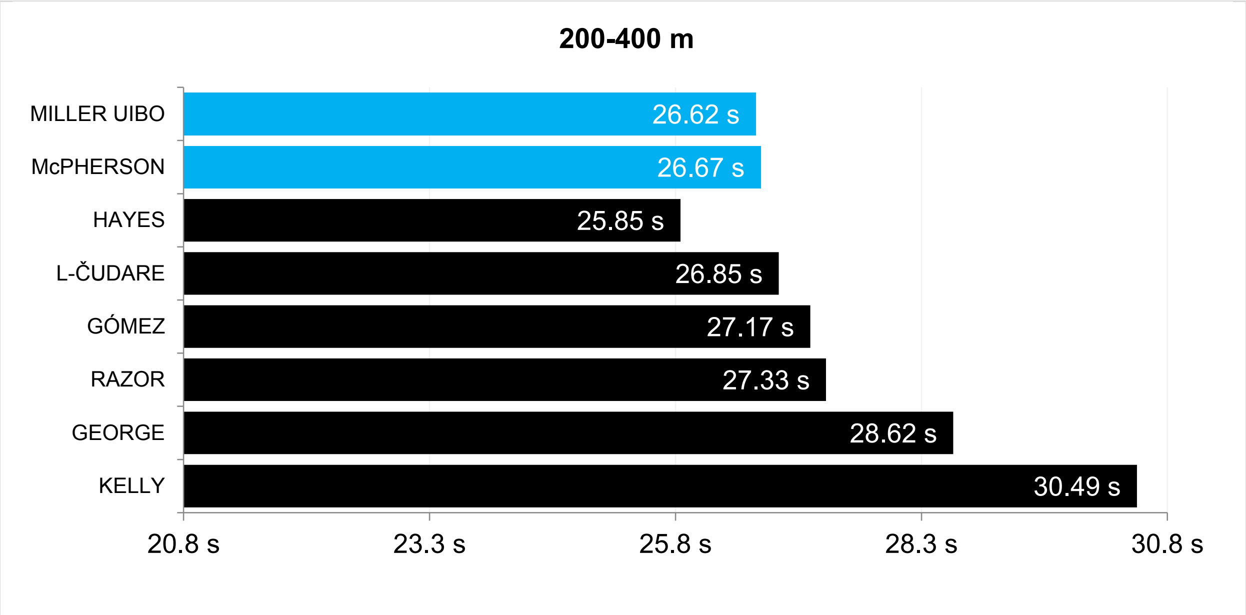

Figure 22. Individual 200-400 m split times.

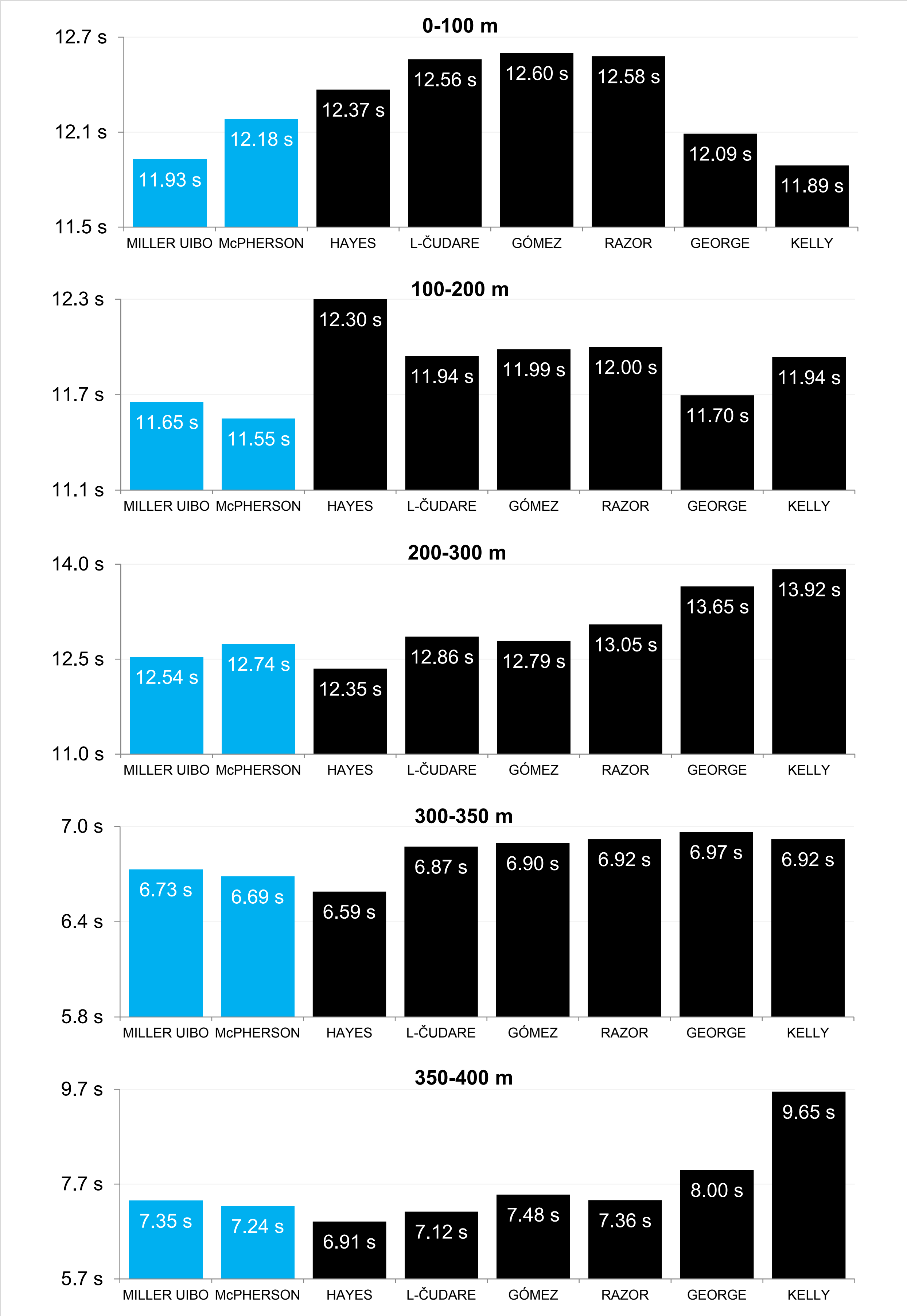

Figure 23. Individual consecutive 100 m split times, and both 50 m times during the home straight.

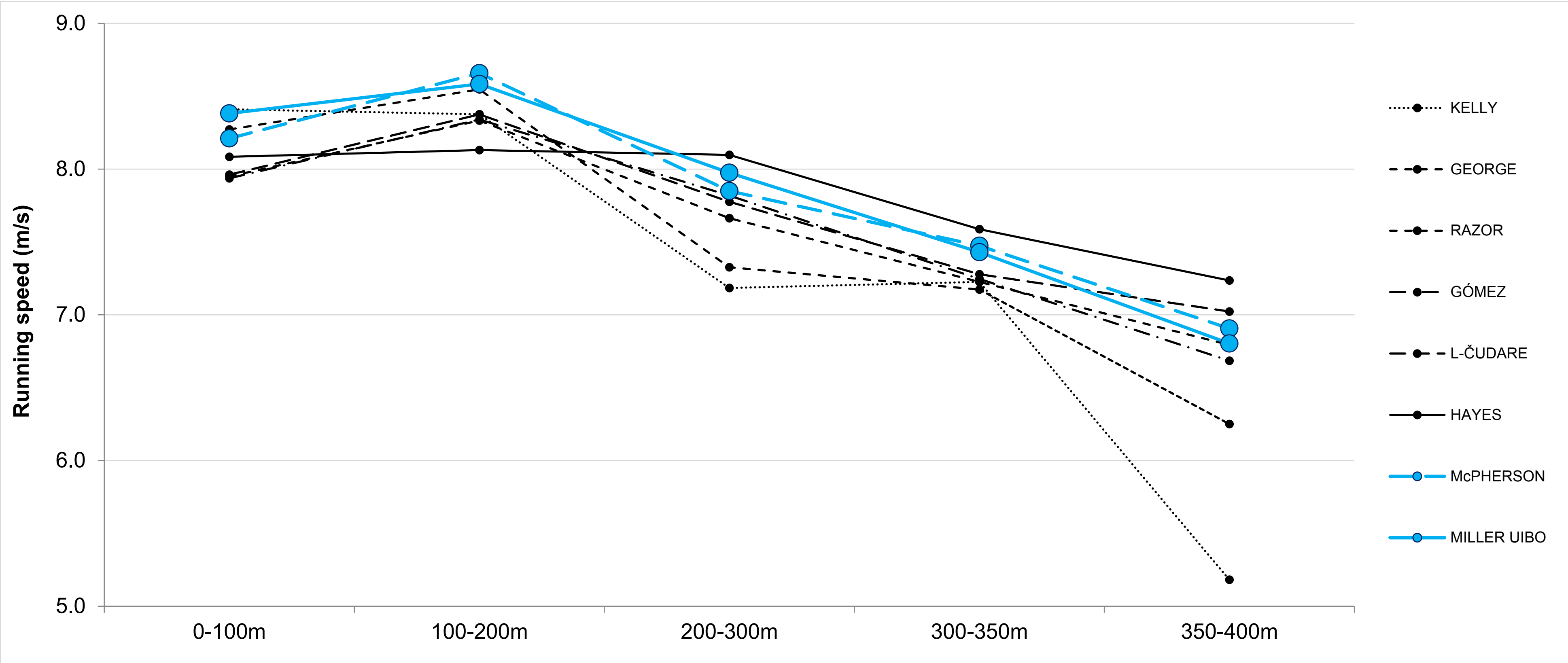

Figure 24. Mean running speed during each consecutive 100 m split, and each 50 m split during the home straight.

Completed steps and step length

The following graphs show step information of individual athletes over progressive 100 m splits for the mean step length and relative to each athlete's stature (Figure 25). The total completed steps for the race and during each 100 m split for each athlete is presented in Figure 26.

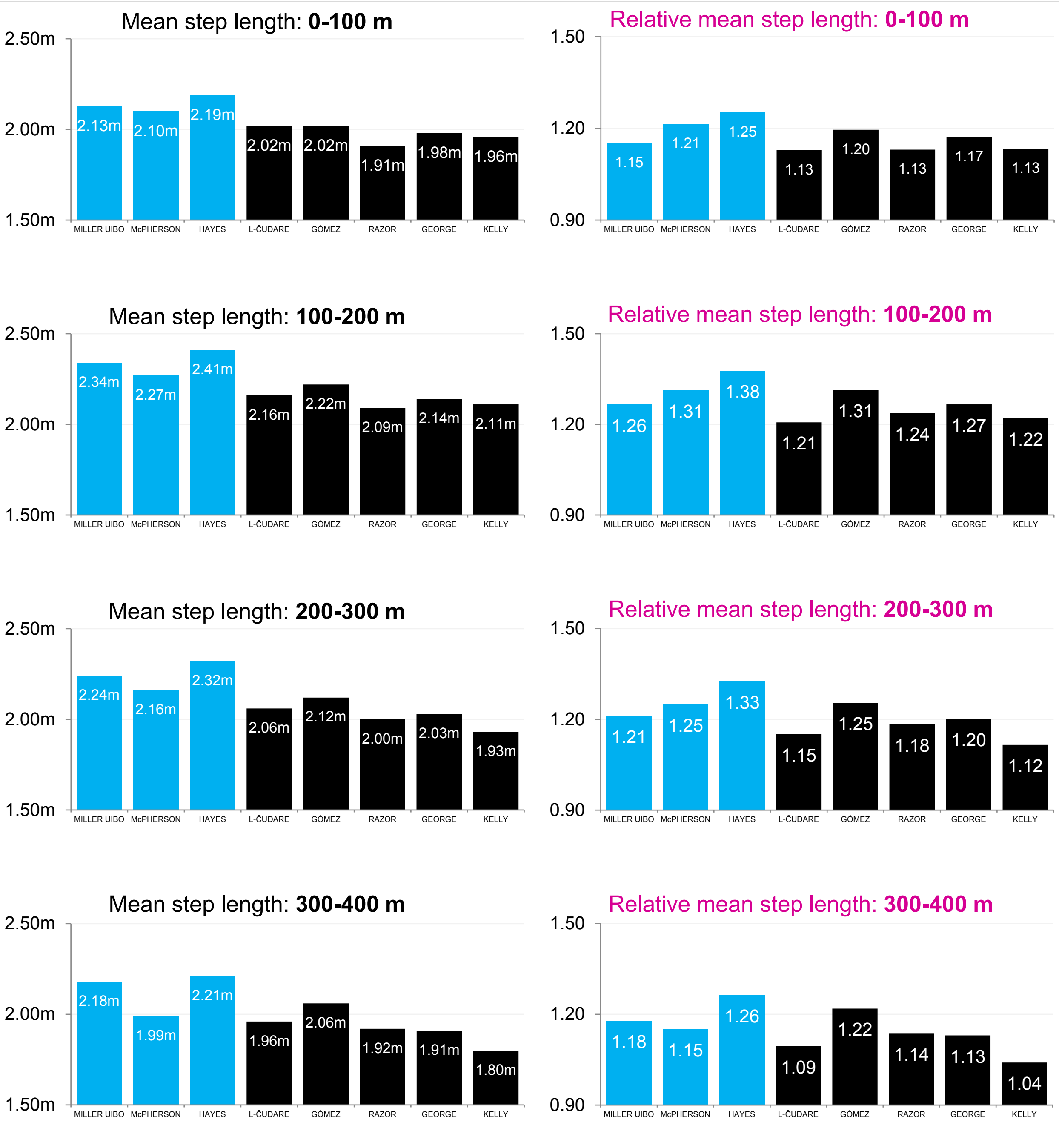

Figure 25. Mean and relative (height) step length during each 100 m split.

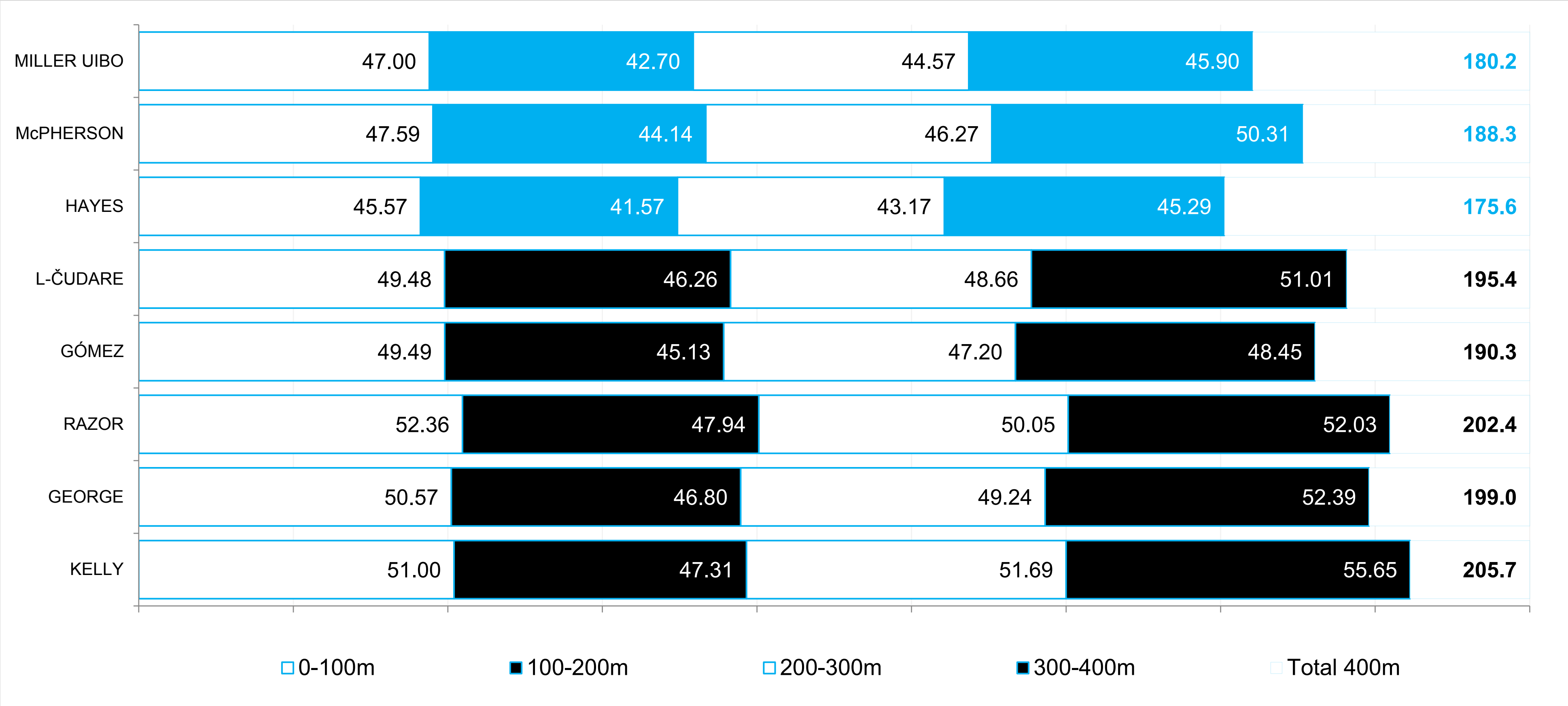

Figure 26. Total completed steps during the race and throughout each consecutive 100 m split.

RESULTS – Semi-Final 2

Performance data

Table 11 below displays the ranking of each athlete before the World Championships across all athletes qualifying for the semi-finals, based on their season's (SB) and personal best (PB) times, and a comparison to their semi-final time.

Table 11. Athletes' ranking based on SB and PB, and comparison to their semi-final performance.

Athlete	*SB rank*	*PB rank*	SEMI-FINAL	*notes*	vs. SB	vs. PB
NASER	*9*	*13*	50.08 s	*Q NR*	–0.49 s	–0.49 s
FELIX	*1*	*1*	50.12 s	*Q*	0.47 s	0.86 s
WILLIAMS-MILLS	*7*	*4*	50.67 s	*q*	0.53 s	1.04 s
JACKSON	*5*	*6*	50.70 s	*q*	0.65 s	0.87 s
JELE	*8*	*11*	51.57 s		1.25 s	1.25 s
AJAYI	*14*	*17*	52.10 s		0.80 s	0.80 s
SHEORAN	*13*	*16*	53.07 s		1.79 s	1.79 s
VASILÍOU	*24*	*24*	53.27 s		1.41 s	1.41 s

Key: *Q = automatic qualifier, q = secondary qualifier, SB = season's best, PB = personal best.*

Positional analysis

Figure 27 shows the relative position of each athlete at each 100 m split throughout the race.

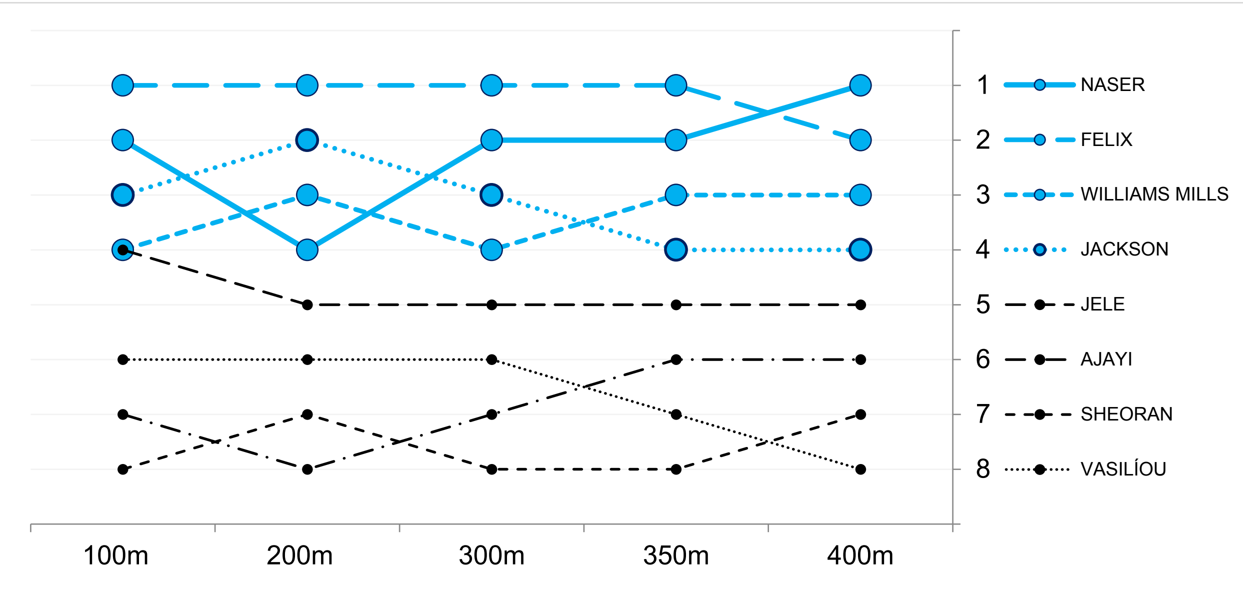

Figure 27. Positions at the end of each 100 m split.

Individual split times

The following graphs display the split times of all athletes over each: 200 m split (Figures 28 and 29), consecutive 100 m splits (note: 0-100 m is displayed without the reaction time) including consecutive 50 m splits during the home straight (Figure 30). The mean speeds over progressive 100 m (from 0-300 metres) and 50 metre (from 300-400 metres) splits are presented in Figure 31.

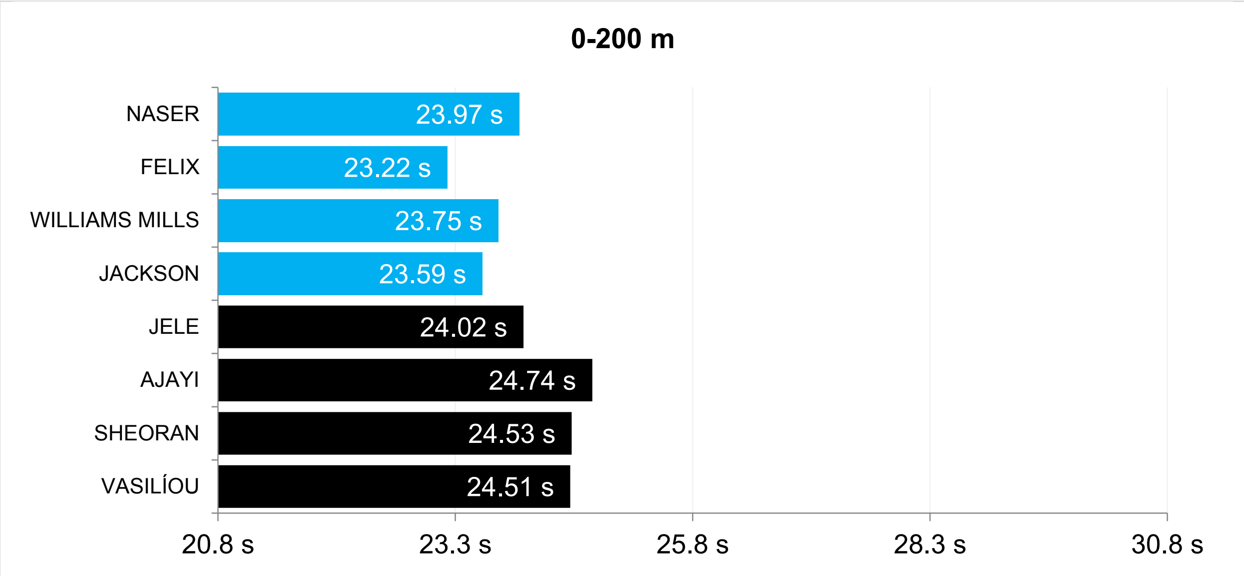

Figure 28. Individual 0-200 m split times (minus reaction time).

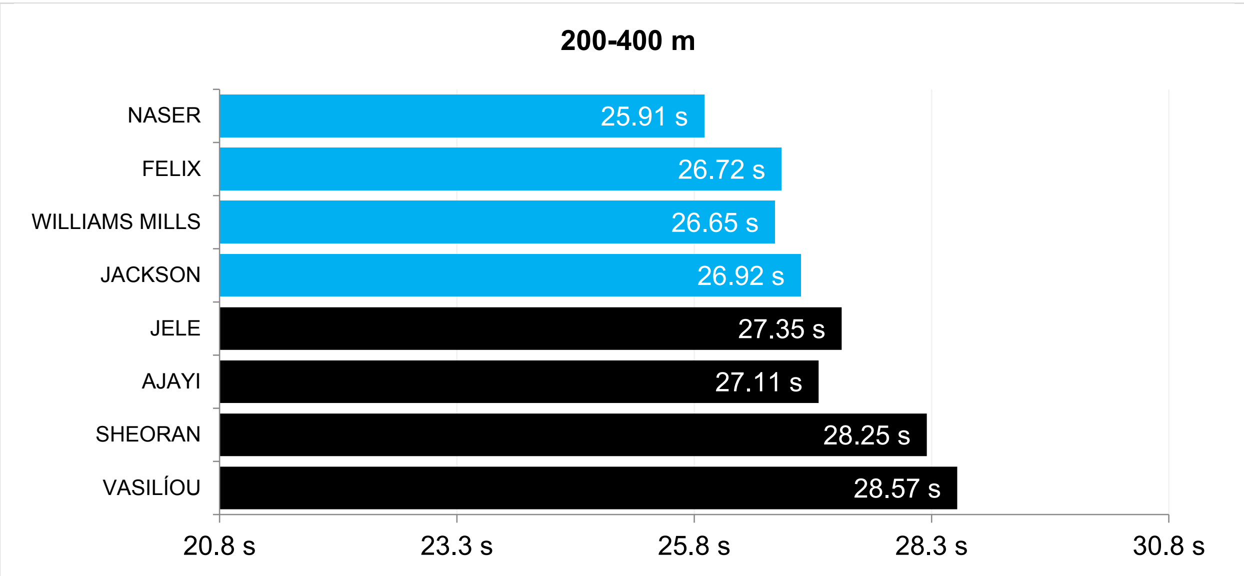

Figure 29. Individual 200-400 m split times.

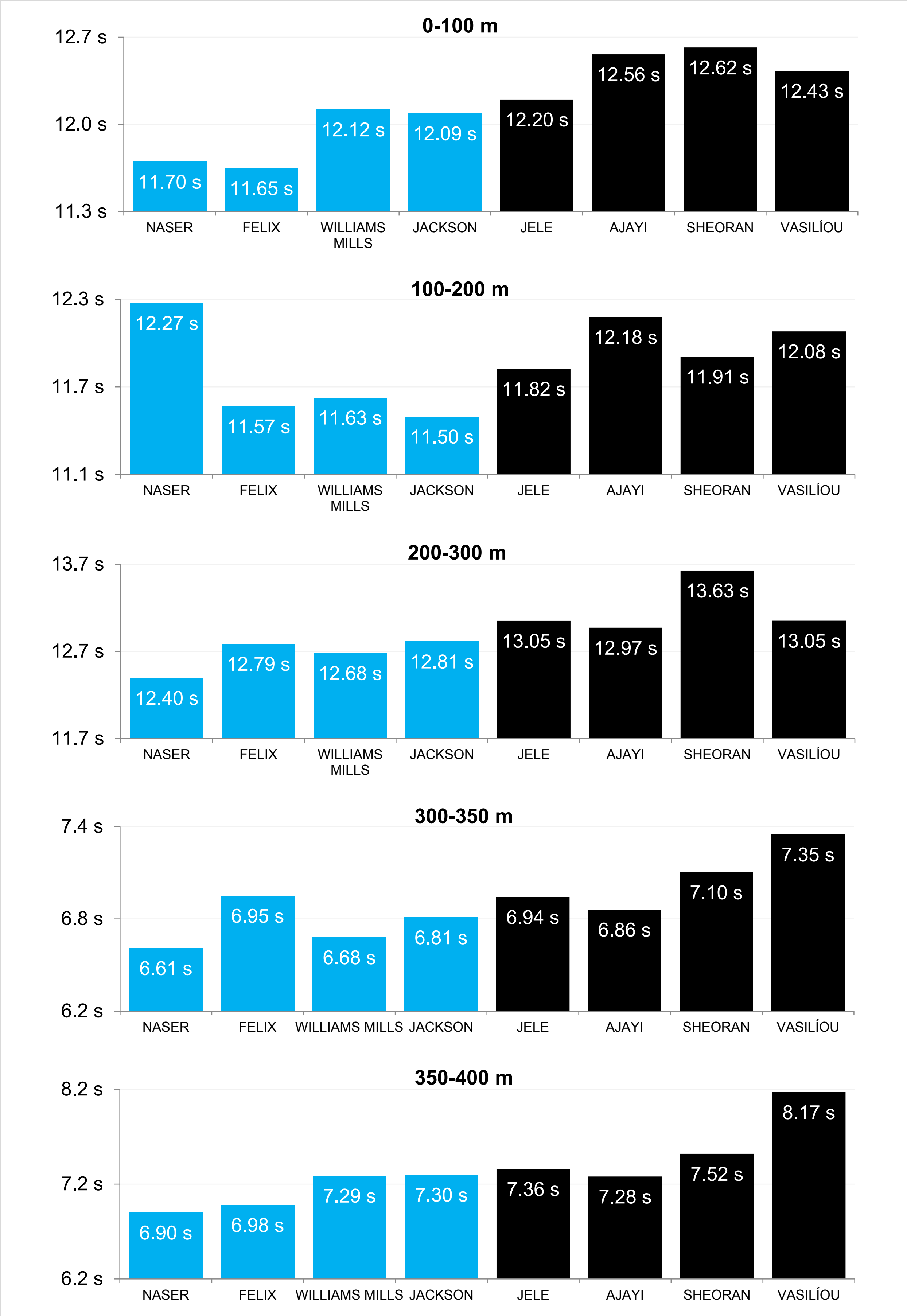

Figure 30. Individual consecutive 100 m split times, and both 50 m times during the home straight.

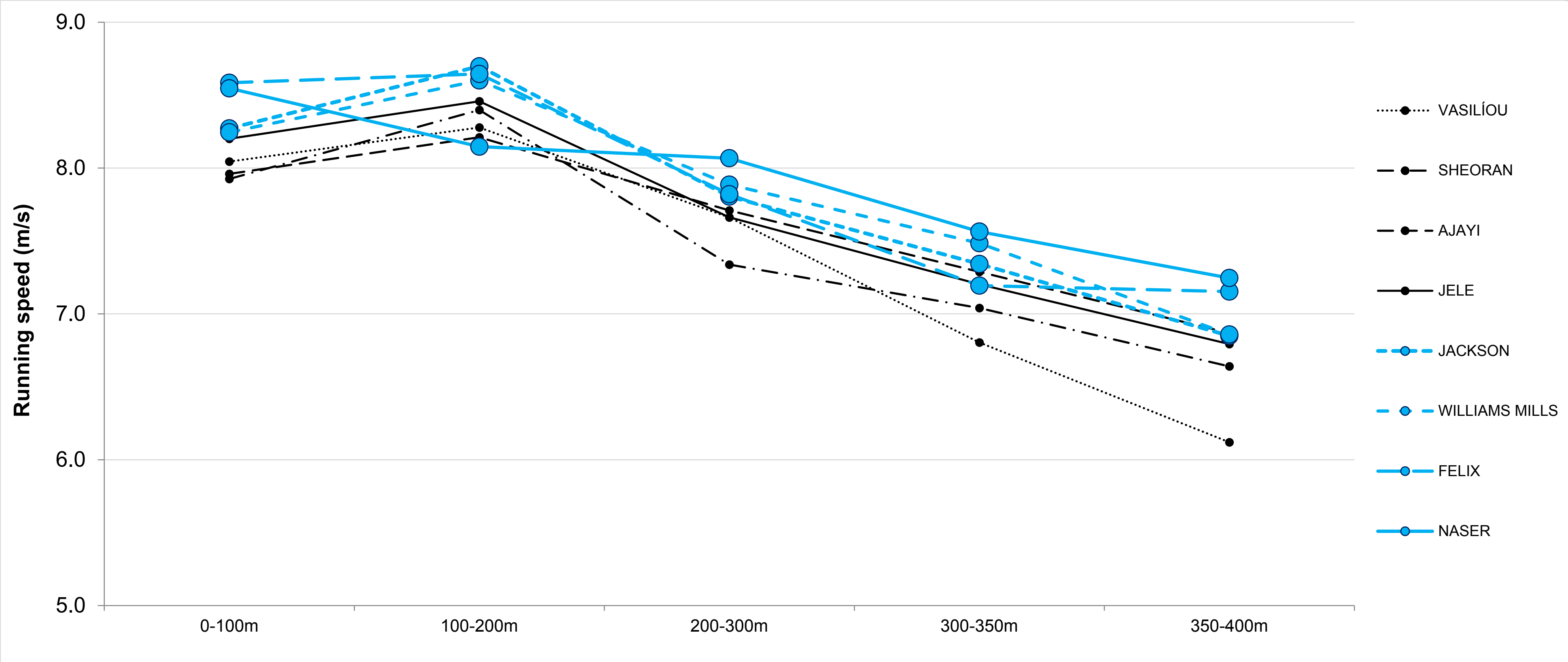

Figure 31. Mean running speed during each consecutive 100 m split, and each 50 m split during the home straight.

Completed steps and step length

The following graphs show step information of individual athletes over progressive 100 m splits for the mean step length and relative to each athlete's stature (Figure 31). The total completed steps for the race and during each 100 m split for each athlete is presented in Figure 32.

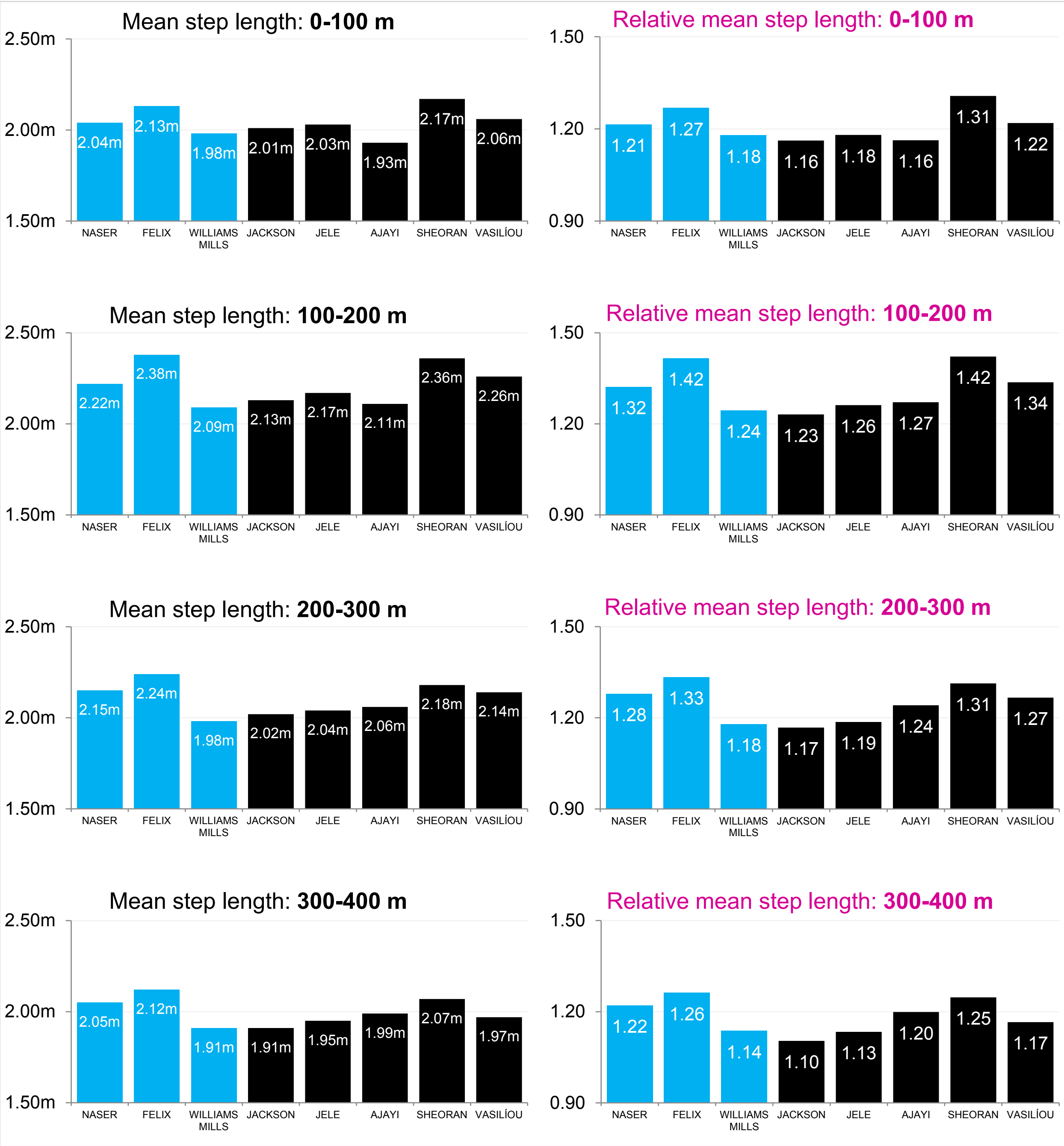

Figure 32. Mean and relative (height) step length during each 100 m split.

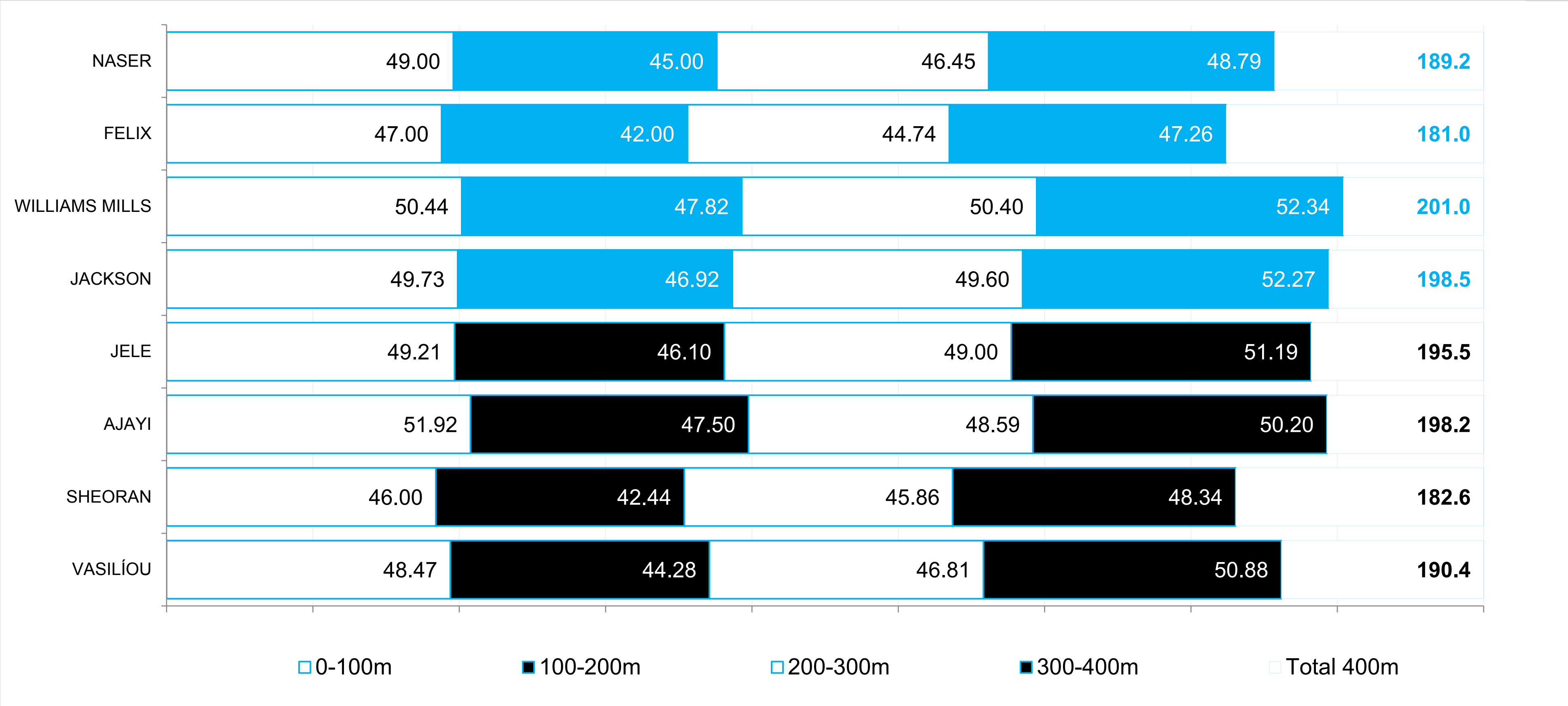

Figure 33. Total completed steps during the race and throughout each consecutive 100 m split.

RESULTS – Semi-Final 3

Performance data

Table 12 below displays the ranking of each athlete before the World Championships across all athletes qualifying for the semi-finals, based on their season's (SB) and personal best (PB) times, and a comparison to their semi-final time.

Table 12. Athletes' ranking based on SB and PB, and comparison to their semi-final performance.

Athlete	*SB rank*	*PB rank*	SEMI-FINAL	*notes*	vs. SB	vs. PB
FRANCIS	*4*	*8*	50.37 s	*Q*	0.41 s	0.43 s
MUPOPO	*12*	*10*	50.60 s	*Q SB*	–0.49 s	0.38 s
GORDON	*6*	*9*	50.87 s		0.74 s	0.74 s
MONTSHO	*15*	*2*	51.28 s	*SB*	–0.09 s	1.95 s
SPELMEYER	*22*	*19*	51.77 s		0.05 s	0.34 s
BAUMGART	*21*	*22*	51.81 s	*.801 s**	0.09 s	0.09 s
CLARK	*23*	*23*	51.81 s	*PB .804 s**	–0.04 s	–0.04 s
BAMGBOSE	*18*	*15*	DQ		0.66 s	1.12 s

Key: *Q = automatic qualifier, q = secondary qualifier, SB = season's best, PB = personal best. .*

Positional analysis

Figure 34 shows the relative position of each athlete at each 100 m split throughout the race.

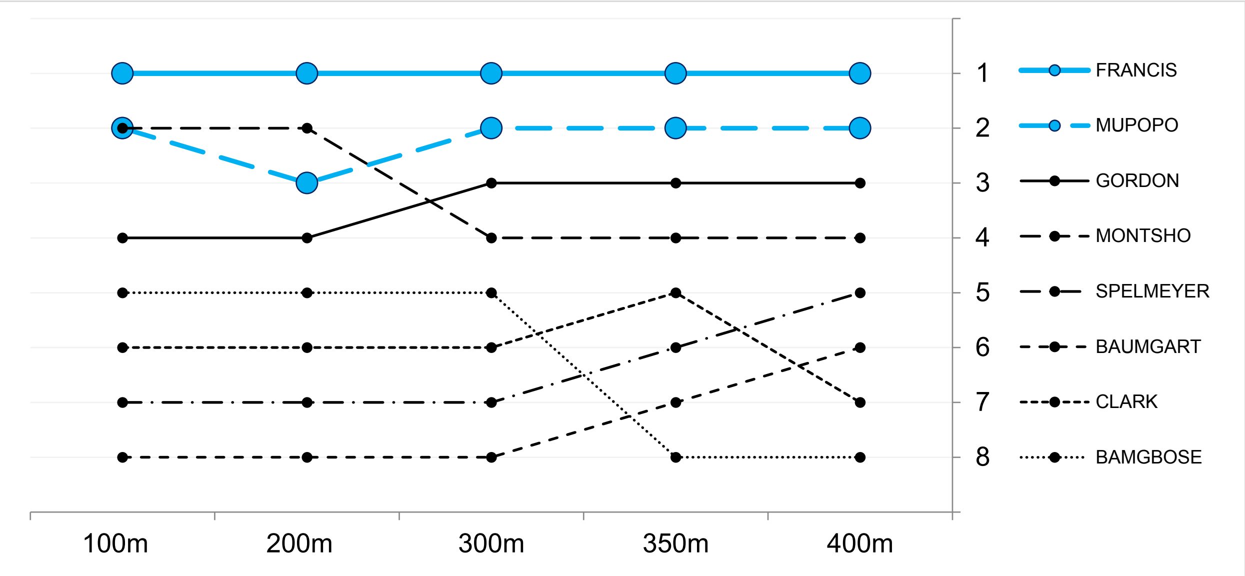

Figure 34. Positions at the end of each 100 m split.

Individual split times

The following graphs display the split times of all athletes over each: 200 m split (Figures 35 and 36), consecutive 100 m splits (note: 0-100 m is displayed without the reaction time) including consecutive 50 m splits during the home straight (Figure 37). The mean speeds over progressive 100 m (from 0-300 metres) and 50 metre (from 300-400 metres) splits are presented in Figure 38.

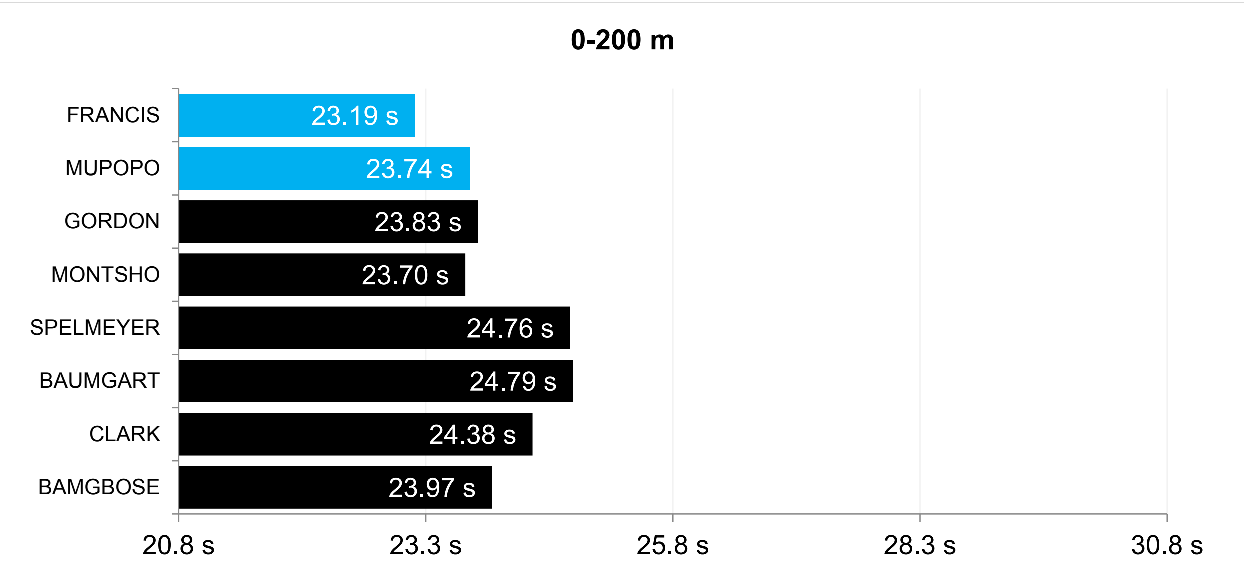

Figure 35. Individual 0-200 m split times (minus reaction time).

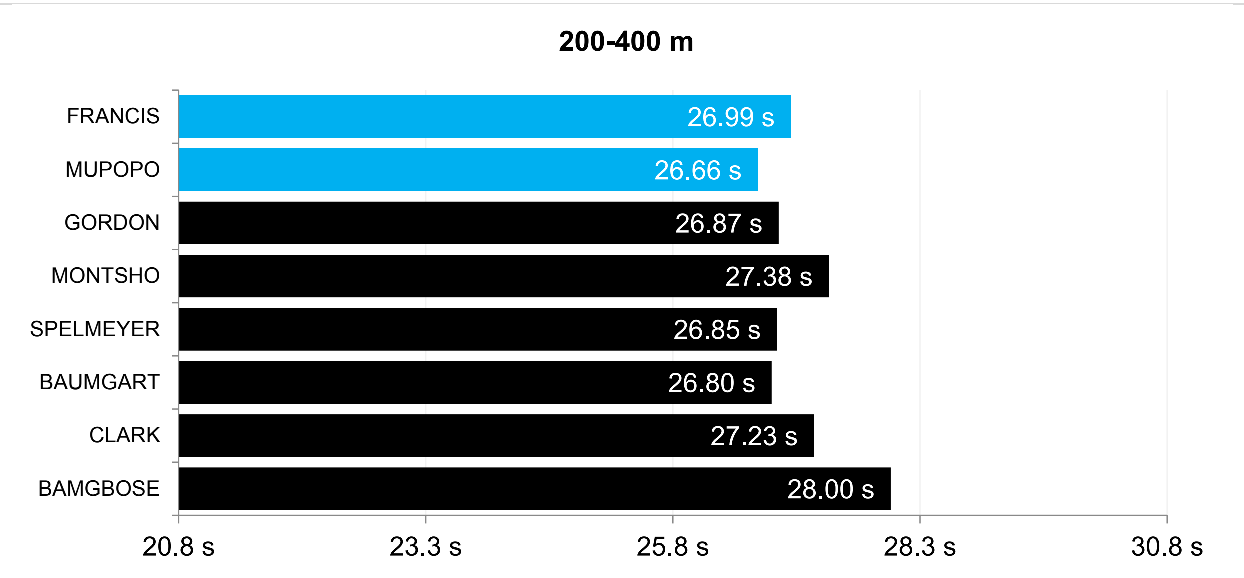

Figure 36. Individual 200-400 m split times.

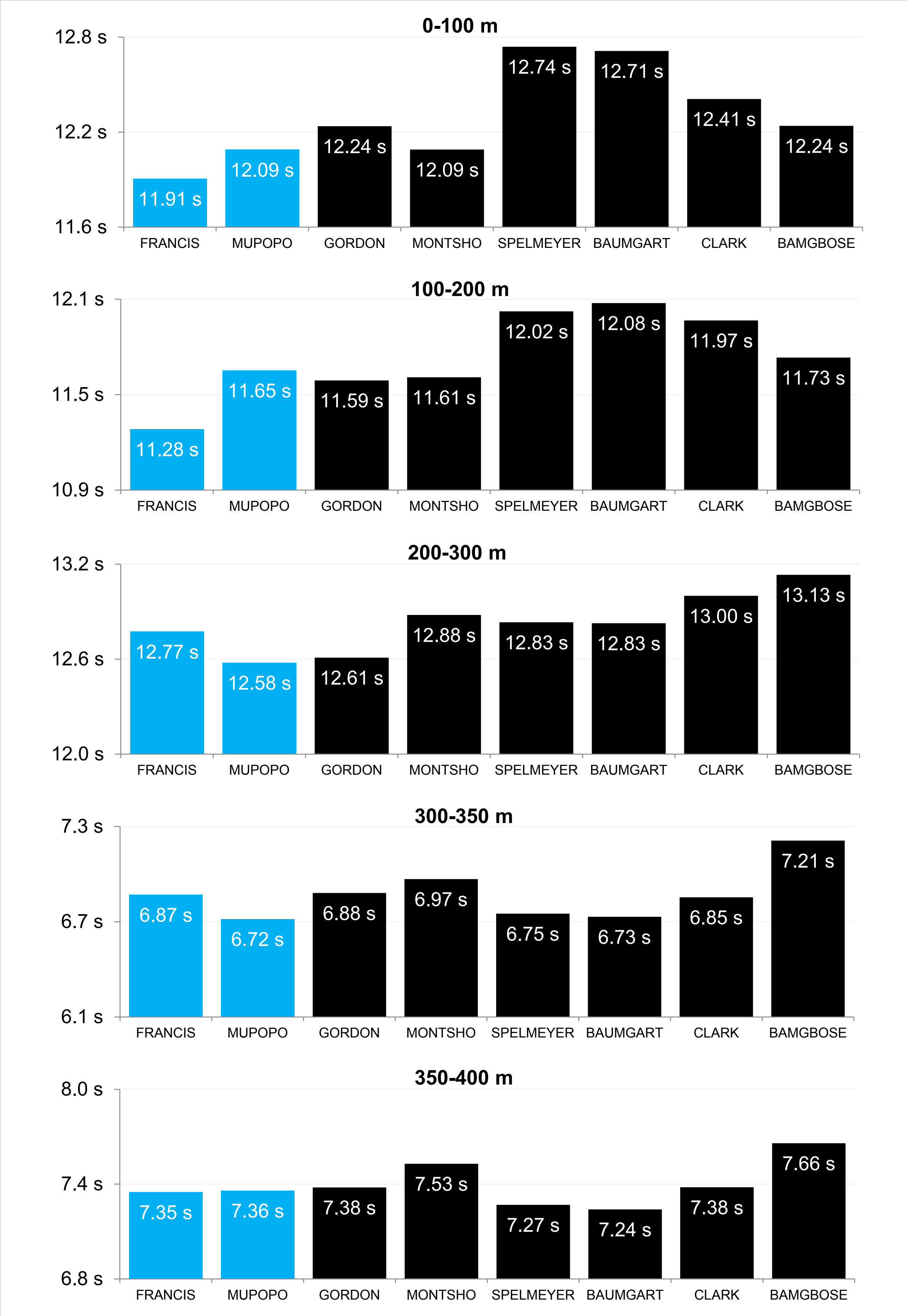

Figure 37. Individual consecutive 100 m split times, and both 50 m times during the home straight.

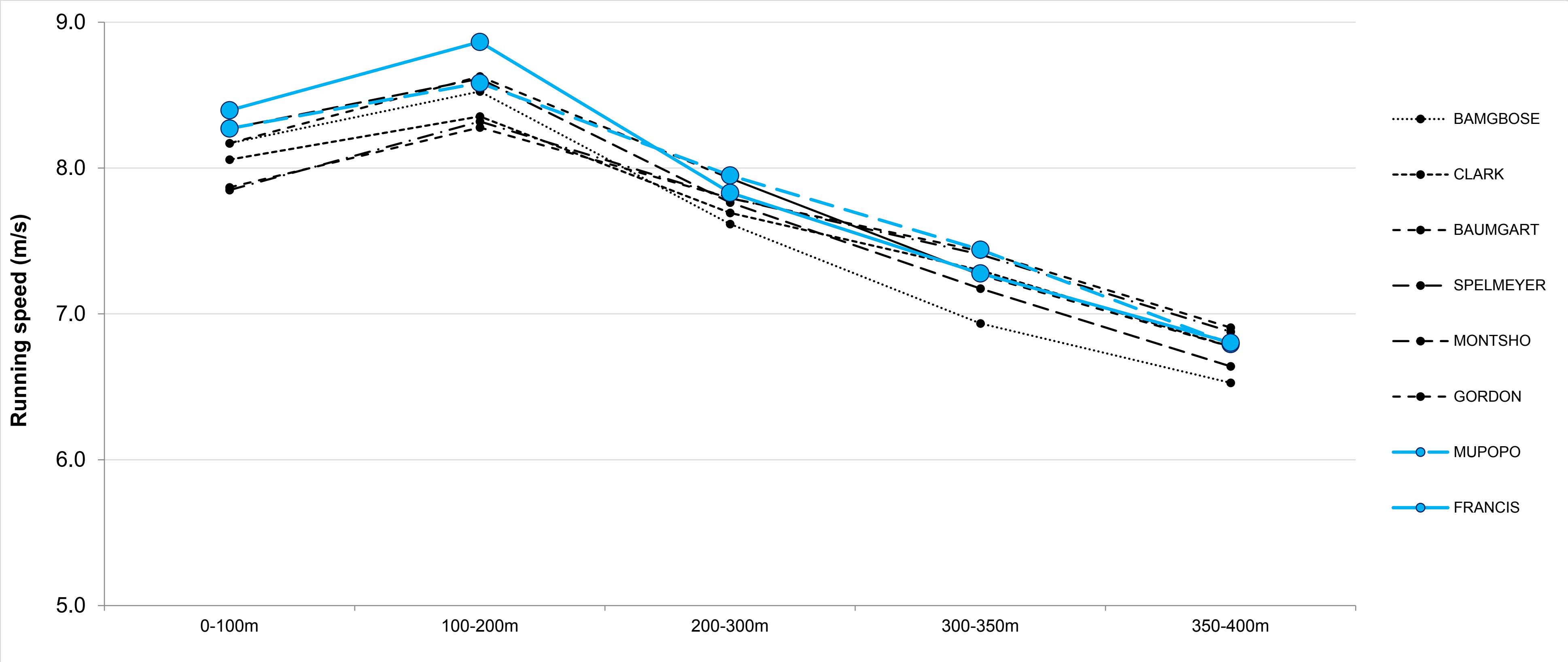

Figure 38. Mean running speed during each consecutive 100 m split, and each 50 m split during the home straight.

Completed steps and step length

The following graphs show step information of individual athletes over progressive 100 m splits for the mean step length and relative to each athlete's stature (Figure 39). The total completed steps for the race and during each 100 m split for each athlete is presented in Figure 40.

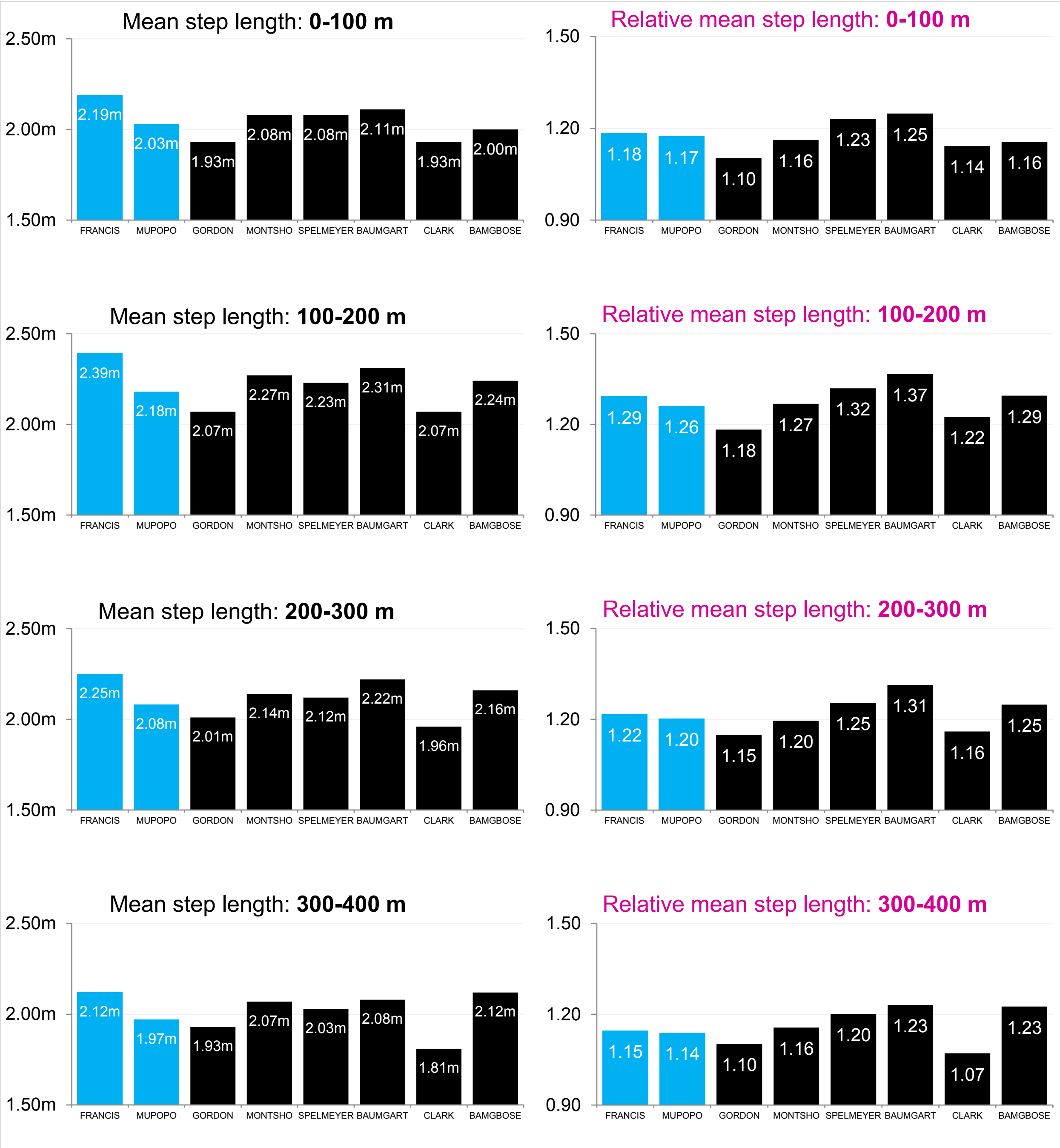

Figure 39. Mean and relative (height) step length during each 100 m split.

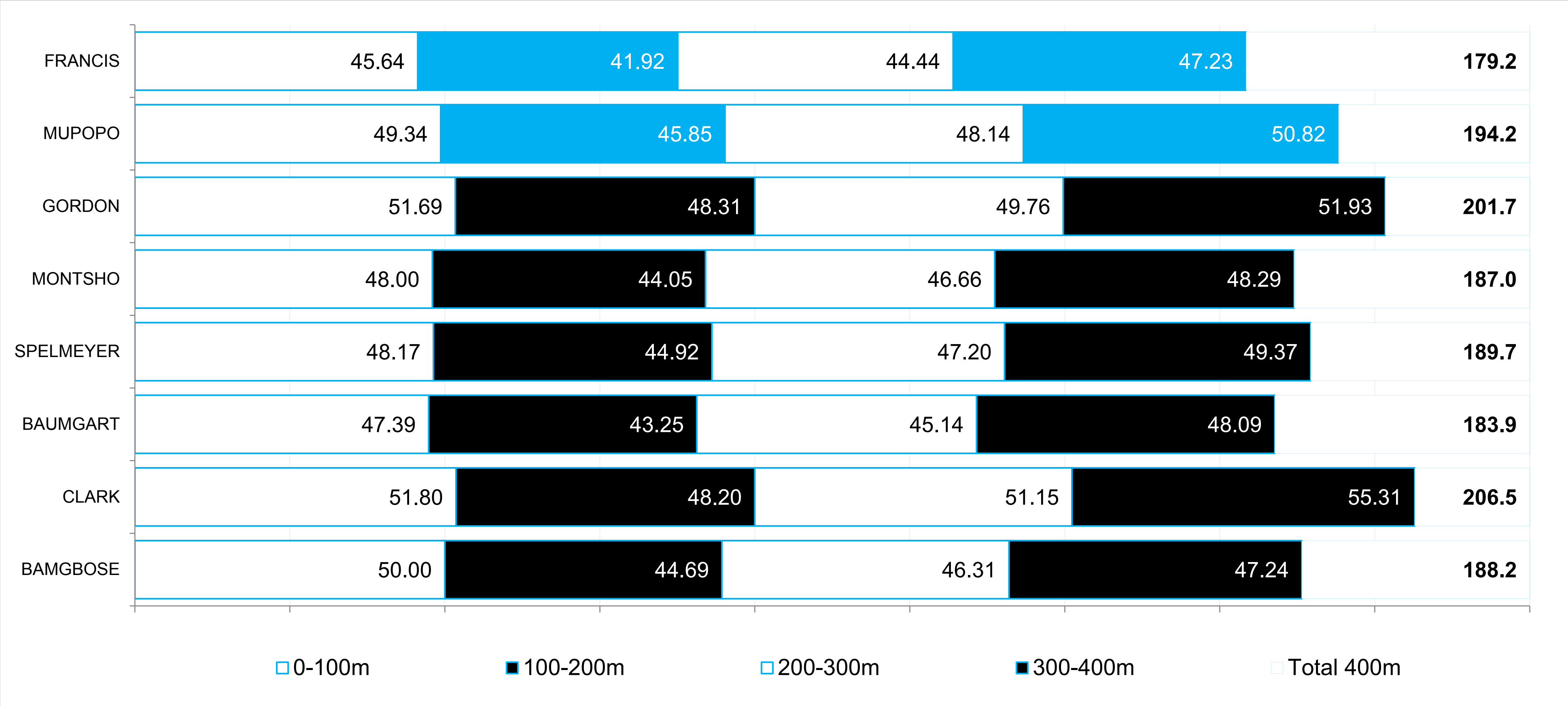

Figure 40. Total completed steps during the race and throughout each consecutive 100 m split.

COACH'S COMMENTARY

Historical analysis and coaching commentary – Pierre-Jean Vazel

The women's 400 m final was expected to be a dual between reigning world champion Allyson Felix and Olympic champion Shaunae Miller-Uibo. It was indeed the case for 360 m (see Figures 5 and 6) before the two favourites faded to 3rd and 4th place, respectively, behind Phyllis Francis who became one of the biggest surprises of the 2017 world championships. Junior Salwa Eid Naser broke her personal best in all her three races in London and got 2nd. Except the gold and silver medallists Francis and Eid Naser, who improved theirs by 0.02 s, all the finalists were far from their personal bests, in a range of 0.80 s to 1.85 s. Interestingly in London, in all women's sprint events, athletes who set PB or SB placed no lower than 4th place, so being able to show one's best form in the final increases odds of getting a medal (see Tables 2 and 3).

Watching the race gives the impression that Felix and Miller-Uibo started too fast and were left without resource in the home stretch. The report presents data recorded during the whole race, so it's now possible to have objective information about the athletes' tactics and compare them with their personal best, and track the consequences on their running mechanics, especially in the last 100 m of the race where fatigue sets in.

Miller-Uibo led Felix by 0.02 s at 100 m in 11.62 s, an extremely fast time considering that it's on pace for a final time of 47.50 s (Vazel, 2010). During the world record of 47.60 s, Marita Koch passed in 11.70 s (attributed times 10.9 s and 11.4 s were incorrect) and she never tried a faster pace than her 11.60 s for a 48.22 s race in Stuttgart (1986). However, the fastest time ever recorded is 11.46 s by Felix at the 2015 world championships (47.00 s pace), where she won in a personal best of 49.26 s. During that race, this incredible first bend was followed by a very cautious 2nd 100 m timed in 11.88 s where she managed to recover, much slower than in London (11.24 s), as placed in lane 5, she chose to follow the fast pace imposed by Miller-Uibo in lane 7. Felix and Miller-Uibo reached the 200 m in 22.88 s and 22.90 s, respectively. Considering that both are sub-22 s runners, this leaves them with 1 sec of speed reserve (the difference between the 200 m intermediate time during a 400 m for an athlete and their performance in a 200 m race). This would be almost ideal if the weather in London had been conducive to sprinting performance, but the rain and the cool temperature (15°C, page 1) contrasted with the good conditions both athletes had when they set their lifetime bests (26°C in Beijing 2015 for Felix and 22°C in Rio 2016 for Miller-Uibo, cf. Seiko 2015 and Omega 2016 official result sheets). A split time less than 23 s sets a pace for a 48.50 s result, which seems to be within reach for both sprinters, but maybe not while fighting with the elements.

Intermediate times for Allyson Felix and Shaunae Miller during the 2017 world championship final and during their personal best races (Yamamoto, 2015 & 2016).

A. Felix	100 m (s)	200 m (s)	300 m (s)	350 m (s)	400 m (s)
WC 2017	11.64	22.88	35.64	42.49	50.08
WC 2015	11.46	23.34	35.67	42.24	49.26
S. Miller Uibo					
WC 2017	11.62	22.90	35.36	42.09	50.49
OG 2016	11.80	22.98	35.34	42.10	49.44

Miller-Uibo was on pace to run her personal best until she collapsed in the last metres. She gave the explanation for this dramatic finish in her post-race interviews: "*I know a lot of people thought I hurt my hamstring or something along that line, but it was kind of weird. I had the race under control and I looked up at the screen and misplaced my foot and completely lost balance*" (Turnbull, 2017).

The kinematic analysis of the running motion at 350 m shows that Felix was the slowest finalist at that point of the race (6.90 m/s). Her step length (2.07 m) and step rate (3.33 Hz) were both lower than what she had done during her fastest last straights in her career (2.20 m and 3.50 Hz for 13 s). Looking at the pattern of the 5 fastest women ever at 400 m, this was also the case for Marita Koch (47.60 s), Jarmila Kratochvilova (47.99 s) and Olga Bryzgina (48.27 s), whereas Marie-José Pérec (48.25 s) speed loss was step length reliant and Tatana Kocembova's (48.59 s) was step rate reliant. Those trends correspond to the most economical ratio between step length and frequency for a given athlete, it lies in the region of the freely chosen one, but is also influenced by different morphologies and coaching orientations (Högberg, 1952; Hofmann, 1986). However, during the course of the 400 m, both step length and frequency decrease along with velocity, with frequency suffering the most, for any group of performers from world to national class (Schäffer, 1989). The kinematic breakdown of Felix's step frequency shows that in London 2017, she had the shortest contact times (0.133 s), both time wise and relative to flight times (0.167 s). While this is ideal in the maximum velocity section of short sprints, such technique is not advisable for the end of a 400 m race because the reduction in force due to fatigue should be balanced with a necessary longer time of contact, since impulse is the product of force and time of application of force. Data from the finalists illustrate this theory: the three finalists that were running at the highest velocity at 350 m (Naser, Francis,and Miller-Uibo) had an average contact time of 0.143 s, longer than of the three slowest (McPherson, Mupopo and McPherson), at 0.136 s; however, they had a shorter flight time – 0.149 s vs. 0.153 s. Furthermore, Felix's shorter step length and longer flight time indicate that she was no longer able to apply force into the ground horizontally enough. By contrast, the mechanics of world record holder Marita Koch were well adapted to the 400 m race, although she was a very fast short sprinter too (personal bests of 7.04 s at 60 m, 10.83 s at 100 m and 21.71 s at 200 m). During a 48.56 s time trial in July 1984, where Koch had a faster last 100 m than during her current world record of 47.60 s (13.26 s vs. 13.38 s), her kinematic parameters at 150 m and 350 m were compared (Müller, 1987). For running velocities of 9.01 m/s an 8.05 m/s, respectively, her flight time decreased from 0.13 s to 0.10 s in order to prevent an excessive loss of step rate and too much vertical oscillation of the centre of mass, while her contact time was lengthened from 0.11 s to 0.15 s, so that there is enough impulse to apply force in its horizontal component and prevent a high loss of step length. Similarly, taking another example in history, during her 47.99 s race, Kratochvilova's flight time was reduced from 53% in the mid-first straight to 49% in the mid-last straight, producing a high efficiency of forward running motion with a vertical displacement of the centre of mass of only 6 cm during a stride cycle (Susanka, 1983).

Olympic champion Miller-Uibo was an example of adaptation of stride pattern between 200 m and 400 m as she was a finalist at both events in London. The main differences, as expected, were a lower knee lift at toe-off, signalling fatigue, and larger extensions of the knee and ankle at toe-off as contact times were longer (0.113 s to 0.147 s for left foot and 0.127 s to 0.160 s for right foot). The average angle extension range was larger during 400 m, from 152° touchdown to 169° at toe-off, compared to what she displayed at 200 m, 156° to 164°. This is similar to Marita Koch during her 1984 time-trial, as her knee angle was about the same at 150 m while running at submaximal speed (155°), and a much larger range at 350 m, from 140° at touchdown to 168° at toe-off. Yet, coaches should be warned about focusing specifically on training muscles (e.g. hip flexors) involved in the above mechanical changes for strength endurance for two main reasons (Martins, 2016). Firstly, as discussed before, the running mechanics under fatigue should not be trained in order to mimic one of sprinting at maximum velocity during a 100 m, since when running 400 m, athletes will look after a more economical pattern and a way to generate enough impulse with longer contact times in order to compensate lower force production due to fatigue. Thus the shift goes from a more vertically orientated force application to a more horizontal one. Secondly, fatigue should be understood from a global, neuromuscular coordination point of view and not as a localised phenomenon on agonist muscles. Indeed, the nervous system adapts and adjusts to local muscular fatigue (e.g. hip flexion) by decreasing the activation of non-fatigued synergist and antagonist muscles in order to maintain an effective coordination and technique (direction of force application) and by increasing the activation of muscles involved in other part of the running motion (e.g. hip extension) in order to limit the decrease of total force application (Brochner Nielsen, 2018). The observation that the knee lift drops with fatigue led coaches to prescribe endurance runs with exaggerated high knees for long sprinters, which became popular from 1955 in Poland (Mach, 1971). However, given the complexity of the neuromuscular coordination with fatigue, the pertinence of training a muscle group in isolation for strength-endurance should be reconsidered. Resistance training using light sleds or gentle hills might be more specific to work on the step adaptations that occur in the last straight of a 400 m race.

Maximum velocity sprinting mechanics may not be a model for 400 m runners due to running economy considerations and necessary adaptations to fatigue. The fact several runners are equally successful at short and long sprints is not contradictory with this statement, as the best are the ones who manage to adapt their stride to the requirements of the distance to run. Furthermore, the final result is more related to the ability to maintain a high velocity in the 200-300 m section of the race, rather than being able to cover the last 100 m faster, since the slope of velocity reduction is the same for all groups of performances from world to national class as shown in studies that included hundreds of subjects (Schäffer, 1989; Vazel, 2010; Yamamoto 2014). However, maximum velocity during 400 m can reach 90% of the maximum velocity recorded during a 100 m and can be achieved as soon as 5.5 s into the 400 m race in the case of the world record holder (Schäffer, 1989), showing the paramount importance of acceleration and top speed workouts for long sprinters.

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Coaching commentary – Ralph Mouchbahani

The data collected for the women's 400 m reveal a trend that seems to underline the importance of speed over endurance for podium performance. Alison Felix has the best 200 m personal best amongst all finalists. It was her fast first 200 m that seemed to secure her the bronze medal (see Figures 5, 7 and 8) as she passed the 200 m mark in first place.

Looking at the importance of the stride pattern (stride length and stride rate), it seems to play a very important role when it comes to efficiency and speed maintenance. The knee angle at touchdown for the non-medallists was on average larger than that of the three podium performance (Tables 6 and 8). Further, the knee angle at toe-off was on average slightly larger for medallists over the non-medallists (Tables 7 and 9). This indicates that the non-medallists were having bigger problems with maintaining proper running mechanics at this stage in the race.

Looking at the individual contact and flight times for each of the finalists around 350 m in Figure 17, along with the step length and swing time data also presented shows that the medallists were travelling faster through the air than the remaining finalists. Covering more distance in less time expresses the efficiency of the stride. Step velocity and relative step length play a major role in the long sprint. Alison Felix managed to secure third position through having a large relative step length (Figure 12, Table 4).

Looking at the individual kinematic characteristics of the finalists around 350 m in Figures 14-17, it becomes apparent that the medallists exhibit a higher relative step length than the non-medallists, whilst they present similar values in other temporal parameters (e.g. contact time, flight time). This allowed the gold and silver medallists to achieve considerably higher step velocities than all the other finalists. As for Felix, her relative step length played a major role as through that, she managed to secure a bronze medal, even though it was obvious that the pacing strategy had a negative effect on the second 200 m performance.

<u>Recommendations for training</u>

1. Special endurance should be linked to proper mechanics.
2. Speed endurance is only effective when proper mechanics and speed have been developed prior.
3. Importance of speed training for 400 m runner secured through proper time and movement patterns of the technical model.

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