BIOMECHANICAL REPORT

FOR THE

IAAF World Championships

LONDON 2017

100 m Women's

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INTRODUCTION

The women's 100 m final and semi-finals took place on Sunday 6th August in good weather conditions. Jamaica's Elaine Thompson was one of the main favourites coming into the championships, having won Olympic gold in Rio 2016 and currently holding a world-leading time of 10.71 s. Dafne Schippers and Marie-Josée Ta Lou would also be likely medal contenders, having come close to Elaine Thompson in some Diamond League events leading up to the world championships. Tori Bowie from the USA was also a potential contender, despite losing out to Elaine Thompson in the 2016 Olympic final. In the end, it was Tori Bowie who narrowly beat Marie-Josée Ta Lou on the line to claim the gold medal with a season's best time of 10.85 s. Ta Lou's silver medal time of 10.86 s was a personal best. The bronze medal went to Dafne Schippers from lane 9, whilst Elaine Thompson was slow out of the blocks and was unable to come back, finishing in 5th place with a time of 10.98 s.

IAAF World Championships

London 4-13 August 2017

RESULTS

100 Metres Women - Final

RECORDS	RESULT	NAME	COUNTRY	AGE	VENUE	DATE
World Record WR	10.49	Florence GRIFFITH-JOYNER	USA	29	Indianapolis (University Stadium), IN	16 Jul 1988
Championships Record CR	10.70	Marion JONES	USA	24	Sevilla (La Cartuja)	22 Aug 1999
World Leading WL	10.71	Elaine THOMPSON	JAM	25	Kingston (NS), JAM	23 Jun 2017

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

6 August 2017 21:51 START TIME 19° C TEMPERATURE 56 % HUMIDITY +0.1 m/s WIND

PLACE	NAME	COUNTRY	DATE of BIRTH	LANE	RESULT		REACTION	Fn
1	Tori BOWIE	USA	27 Aug 90	7	10.85	SB	0.182	
2	Marie-Josée TA LOU	CIV	18 Nov 88	4	10.86	PB	0.180	
3	Dafne SCHIPPERS	NED	15 Jun 92	9	10.96		0.155	
4	Murielle AHOURÉ	CIV	23 Aug 87	8	10.98 (.976)		0.184	
5	Elaine THOMPSON	JAM	28 Jun 92	6	10.98 (.978)		0.200	
6	Michelle-Lee AHYE	TTO	10 Apr 92	3	11.01		0.151	
7	Rosangela SANTOS	BRA	20 Dec 90	5	11.06		0.150	
8	Kelly-Ann BAPTISTE	TTO	14 Oct 86	2	11.09		0.142	

Timing and Measurement by SEIKO AT-100-W-f--1--.RS1..v1 Issued at 21:54 on Sunday, 06 August 2017

Official Partners

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METHODS

Six vantage locations for camera placement were identified and secured. Each location 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 starting line to the 90 m line) whilst the sixth location was located within the IAAF VIP outdoor area overlooking the finish line from a semi-frontal angle (Figure 1).

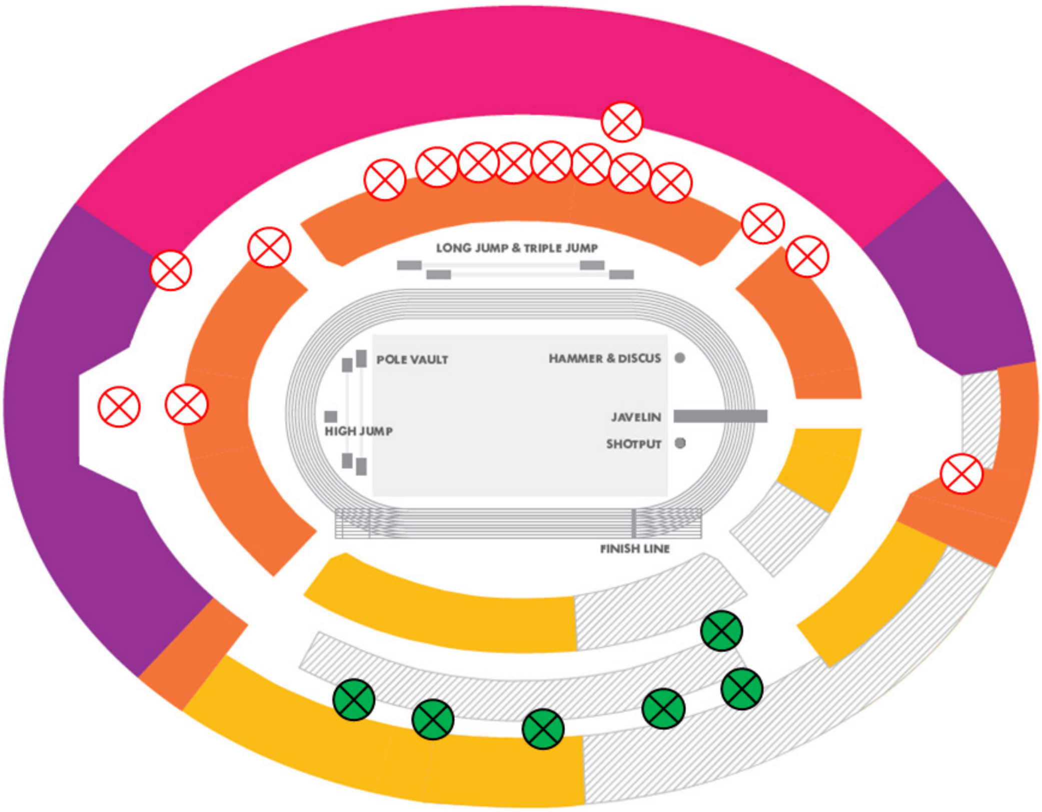

Figure 1. Camera layout for the women's 100 m indicated by green in-filled circles.

Three separate calibration procedures were conducted before and after each competition. First, a series of nine interlinked training hurdles were placed at each 10 m line on the track ensuring that the crossbar of each hurdle, covered with black and white tape, was aligned with the track's transverse line. Second, a rigid cuboid calibration frame (Figure 2) was positioned on the running track between the 47-metre mark and the 55.5-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. 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. Third, an additional volume spanning all 9 lanes was defined for the final metres of the race through a calibration process similar to the middle section.

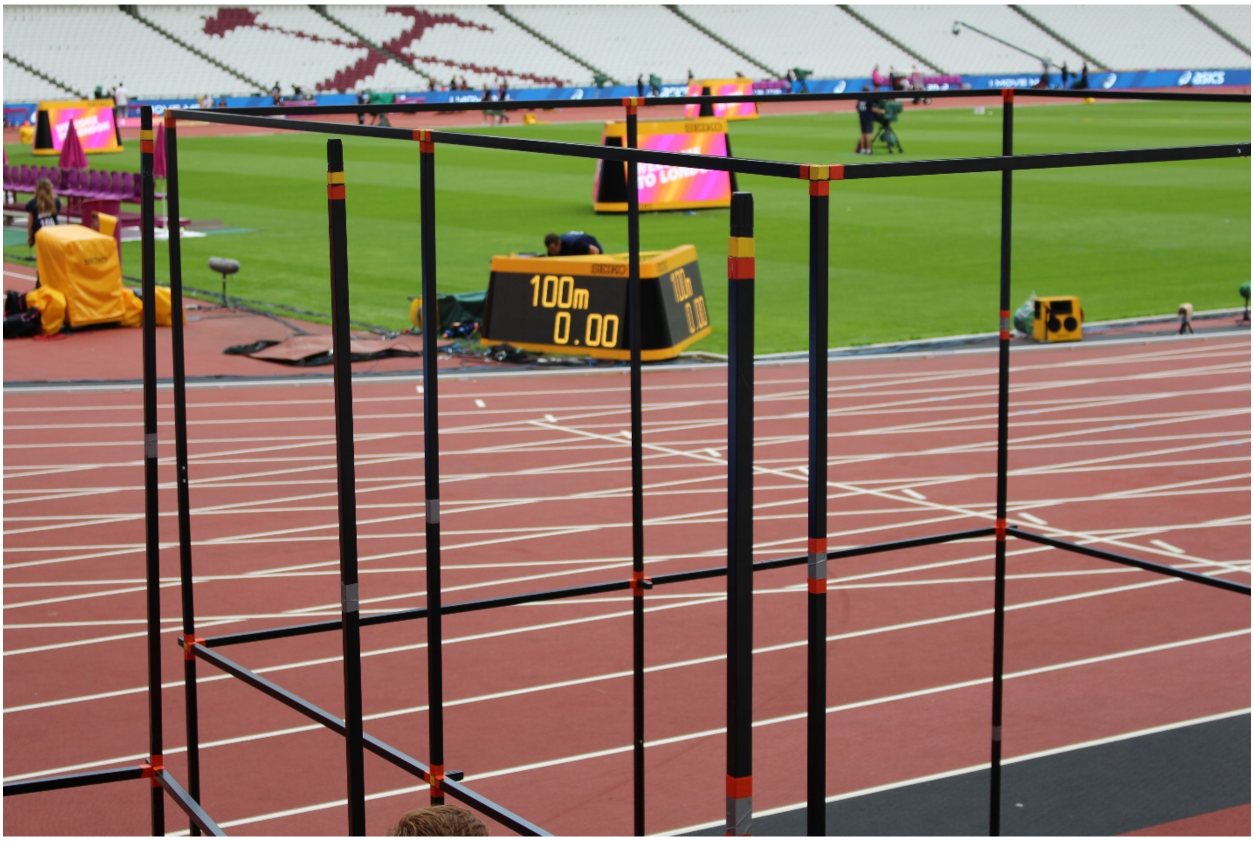

Figure 2. The calibration frame was constructed and filmed before and after the competition.

A total of 23 high-speed cameras were employed to record the action during the 100 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. Furthermore, four Fastec TS3 cameras operating at 250 Hz (shutter speed: 1/1000; ISO: 1600; SXGA: 1280x1024 px) were recording motion within the same middle section volume by focusing on the lower body segments. Finally, two additional Fastec TS3 (250 Hz) and two Sony RX10 M3 (100 Hz) cameras operating as two separate pairs were employed to record motion in the final section of the race.

Figure 3. Action from the 100 m women's final.

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. Digitising started 15 frames before the beginning of the stride and completed 15 frames after to provide padding during 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 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. De Leva's (1996) body segment parameter models were used to obtain data for the whole body centre of mass and for key body segments of interest. 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.

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 temporal kinematic characteristics were processed through SIMI Motion by using the 100 Hz and 250 Hz footage respectively whilst the digitising process for the final section of the race was centred upon critical events (e.g., touchdown and toe-off) rather than an analysis of the full sequence throughout the calibration volume.

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

Variable	Definition
Race position	Ranking of each athlete in the race at each 10 m interval.
Split time	Time taken to complete each 10 m interval.
Mean speed#	Mean speed throughout each 10 m interval based on split time.
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).
Step width	Mediolateral distance between two consecutive foot contacts (foot tips).
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.
CM horizontal velocity#	Mean horizontal CM velocity over one step.
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.
CM contact distance	The horizontal distance that the CM travelled during a single ground contact.
Braking phase	The time period of the downward phase of the CM during ground contact.
Propulsive phase	The time period of the upward phase of the CM during ground contact.
Height CM	Vertical distance between the CM and the running surface during ground contact.
Vertical CM velocity	The vertical component of the CM velocity during ground contact.
Foot horizontal velocity	The horizontal component of the foot CM velocity.
Foot vertical velocity	The vertical component of the foot CM velocity.
Resultant foot swing velocity	The resultant linear velocity of the foot CM during the swing phase.
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.
Angular velocity (hip, knee, ankle)	The angular velocities of key lower body joints.

Note: *CM = centre of mass.*

Velocity calculations: please note that the three velocities (marked in Table 1 with $^{\#}$) have been obtained through different calculation techniques and therefore should not be compared against each other as they are expected to display slightly different values. For instance, the mean speed is purely a calculation based on split time data, the step velocity is derived from step length and step time, whereas the CM horizontal velocity has been calculated through full-body digitising. We consider the CM horizontal velocity as being the most accurate, however, we present all three, as they will help the reader to form a complete view of speed profiles and compare performance with previous studies.

RESULTS – FINAL

The following section of results includes data from the women's 100 m final, which have been derived from split time analysis and key temporal and kinematic data at specific stages of the race.

Positional analysis

Whilst the optical axes of the split cameras were perpendicular to the running direction, the fact that we had capacity for only five locations along the home straight meant that the cameras were positioned strategically at 20 m intervals. Whilst this introduces potential perspective and parallax errors for some camera views, the analysis was conducted on an individual-athlete basis (measured as the point at which the acromion process coordinate crosses the split line) and triangulated with television footage (official IAAF digital feed) and other sources. Furthermore, in the zones where the 250 Hz and 150 Hz cameras were operating, these cameras were used to corroborate the athletes' race positions.

Taking into account the aforementioned limitations, we feel that this was the best approach to accurately capture the split times based on the number of camera positions we had available. However, a movement towards a technology that incorporates either timing chips on athletes' bibs or a sophisticated local positioning system would lead to potentially more accurate and instantaneous split times.

The following figure shows each finalist's race position at each 10 m interval, based on cumulative split time data. Note that positional analysis (Figure 4) is based on time to three decimal places. This should be considered when comparing race position with cumulative split times (Table 2.2).

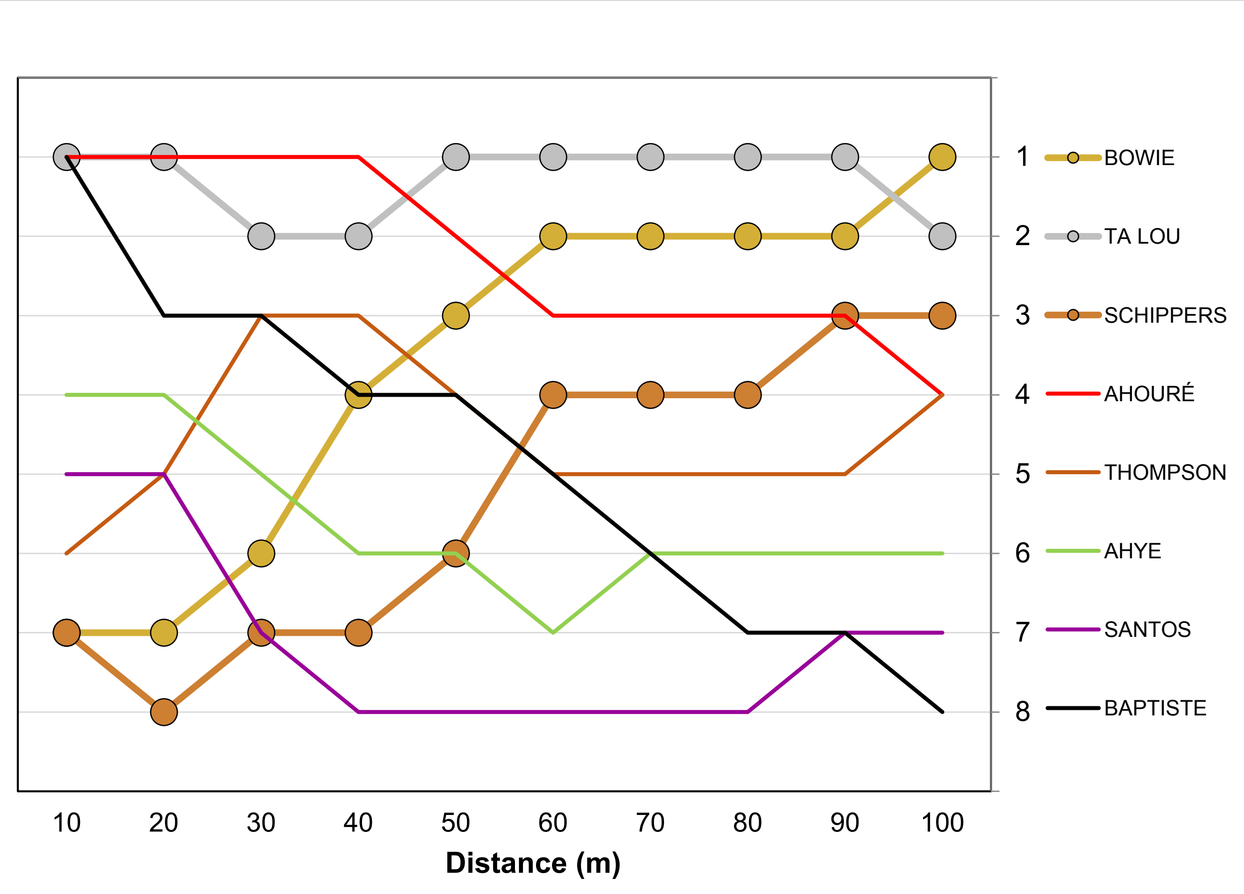

Figure 4. Race position of the finalists at each 10-metre split. Medallists have been highlighted in respective medallist colours.

Individual split times

Table 2.1. Split times every 10 metres for each athlete.

Athlete	RT	0-10 m	10-20 m	20-30 m	30-40 m	40-50 m	50-60 m	60-70 m	70-80 m	80-90 m	90-100 m	0-100 m
BOWIE	0.182	2.07	1.15	1.02	0.94	0.93	0.93	0.94	0.95	0.95	0.97	10.85
TA LOU	0.180	2.01	1.14	1.04	0.96	0.94	0.92	0.93	0.96	0.97	0.99	10.86
SCHIPPERS	0.155	2.07	1.16	1.02	0.95	0.94	0.93	0.94	0.97	0.98	1.00	10.96
AHOURÉ	0.184	2.01	1.14	1.03	0.96	0.96	0.95	0.95	0.97	0.99	1.02	10.98
THOMPSON	0.200	2.06	1.15	1.01	0.95	0.96	0.95	0.96	0.97	0.98	0.99	10.98
AHYE	0.151	2.02	1.17	1.04	0.96	0.95	0.95	0.96	0.97	0.99	1.00	11.01
SANTOS	0.150	2.04	1.17	1.04	0.96	0.96	0.95	0.96	0.97	1.00	1.01	11.06
BAPTISTE	0.142	2.01	1.16	1.05	0.96	0.95	0.95	0.97	0.99	1.01	1.04	11.09

Note: *RT = reaction time. The gold shaded cells indicate the fastest splits for that section. Split times include RT and rounded to two decimal places.*

Table 2.2. Cumulative split times every 10 metres for each athlete.

Athlete	RT	-10 m	-20 m	-30 m	-40 m	-50 m	-60 m	-70 m	-80 m	-90 m	-100 m
BOWIE	0.182	2.07	3.22	4.24	5.18	6.11	7.04	7.98	8.93	9.88	10.85
TA LOU	0.180	2.01	3.15	4.19	5.15	6.09	7.01	7.94	8.90	9.87	10.86
SCHIPPERS	0.155	2.07	3.23	4.25	5.20	6.14	7.07	8.01	8.98	9.96	10.96
AHOURÉ	0.184	2.01	3.15	4.18	5.14	6.10	7.05	8.00	8.97	9.96	10.98
THOMPSON	0.200	2.06	3.21	4.22	5.17	6.13	7.08	8.04	9.01	9.99	10.98
AHYE	0.151	2.02	3.19	4.23	5.19	6.14	7.09	8.05	9.02	10.01	11.01
SANTOS	0.150	2.04	3.21	4.25	5.21	6.17	7.12	8.08	9.05	10.05	11.06
BAPTISTE	0.142	2.01	3.17	4.22	5.18	6.13	7.08	8.05	9.04	10.05	11.09

Note: *RT = reaction time. Split times include RT and rounded to two decimal places.*

Speed analysis

Figure 5 (below) shows the mean speed over each 10-metre split for each of the finalists. This was calculated based on the time taken to complete each split.

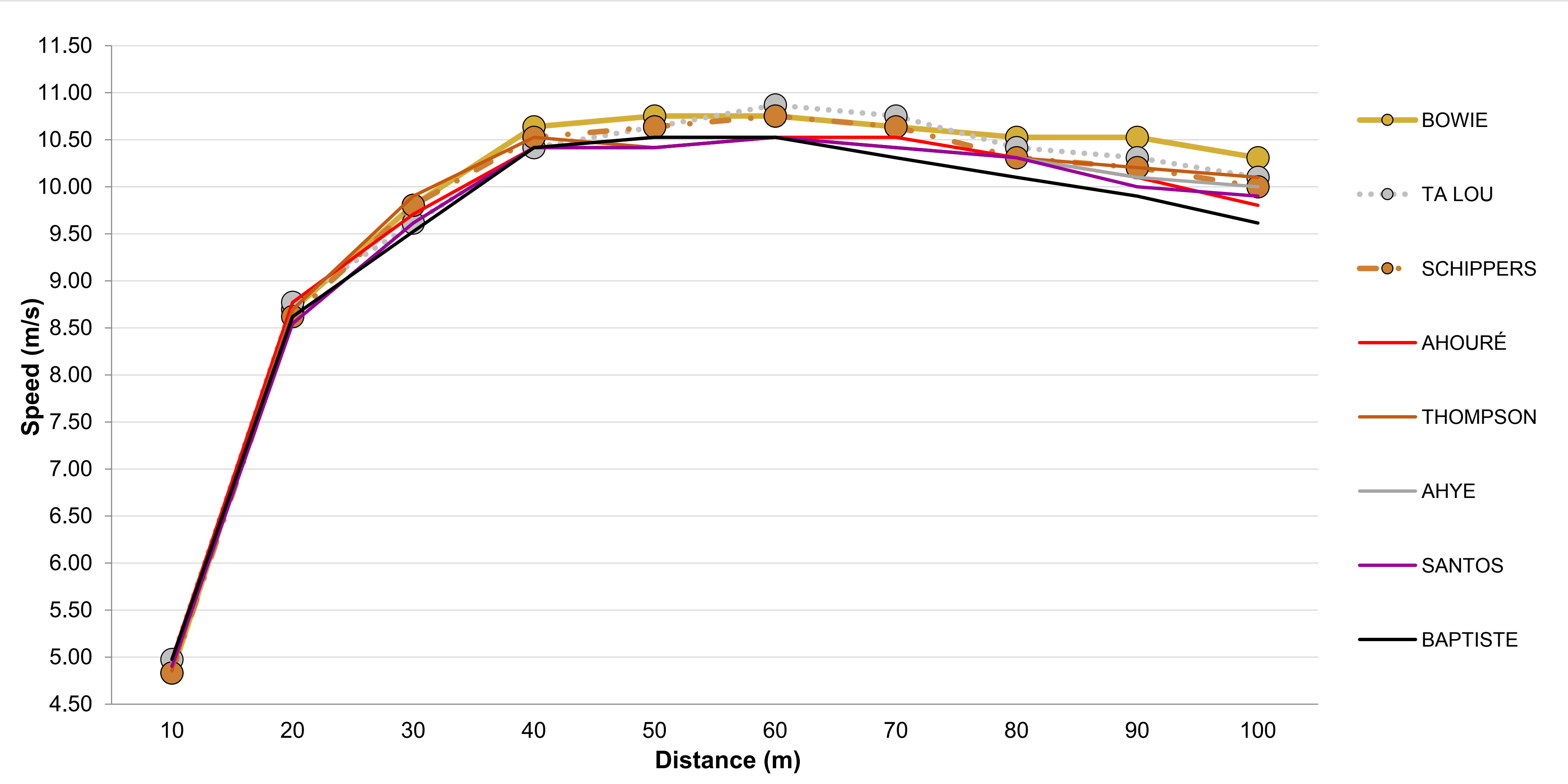

Figure 5. Mean speed over each 10-metre split.

Figures 6 and 7 (below) display the mean speed separately for the medallists (Figure 6) and the remaining 5 finalists (Figure 7).

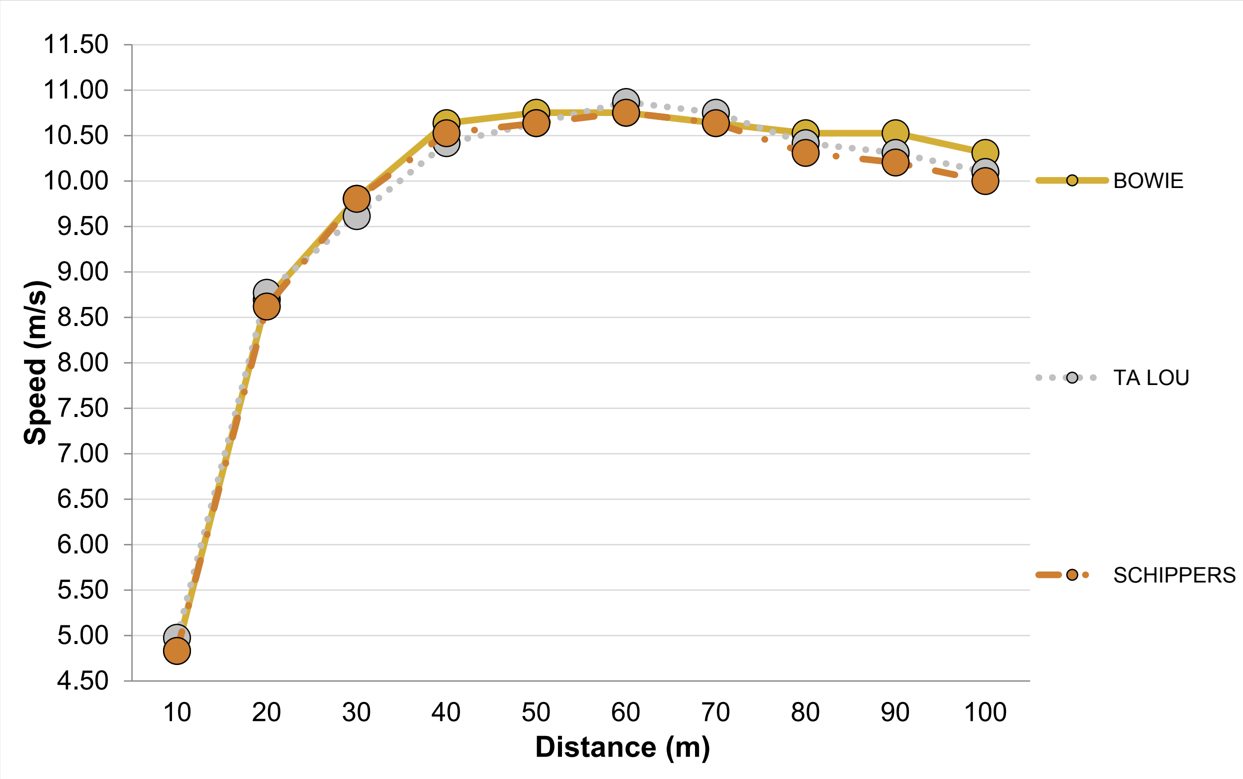

Figure 6. Mean speed over each 10-metre split – medallists only.

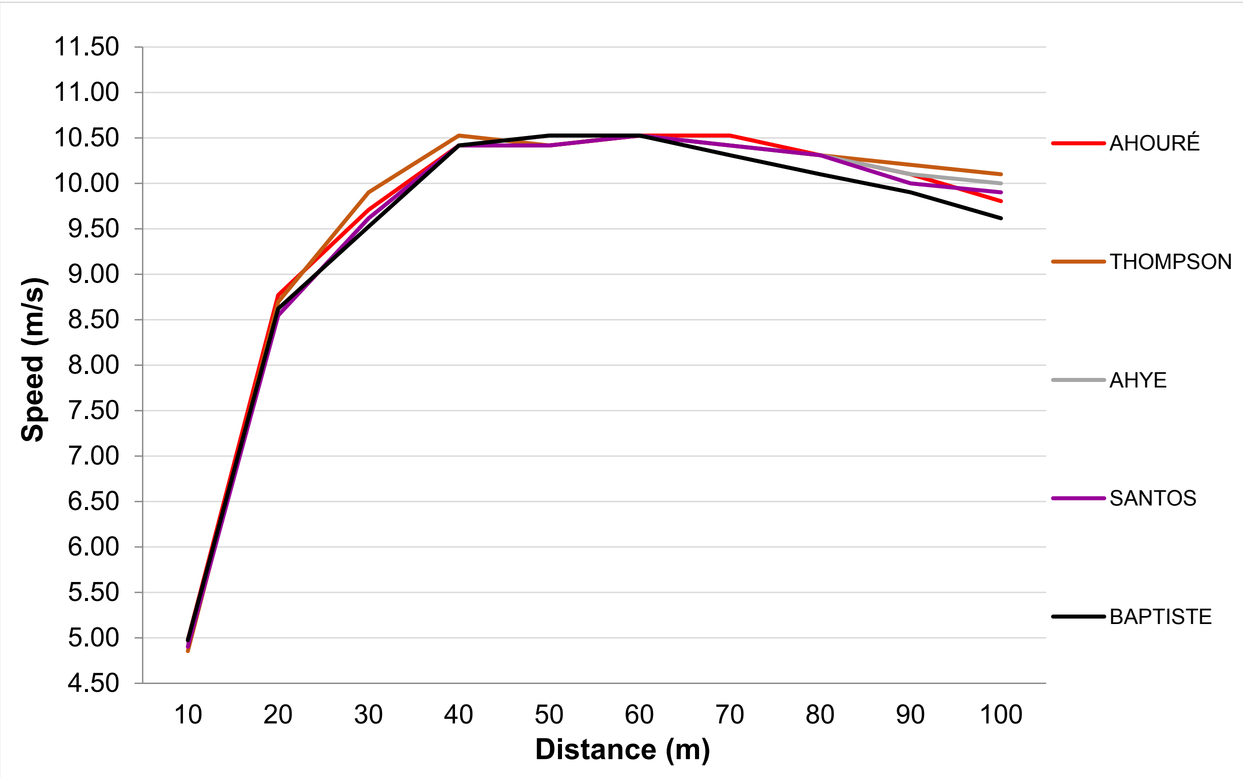

Figure 7. Mean speed over each 10-metre split – remaining five finalists.

Step length analysis

The following two figures display mean step length, based on step count data. Data are displayed as both absolute lengths and lengths relative to body height (1.00 = body height).

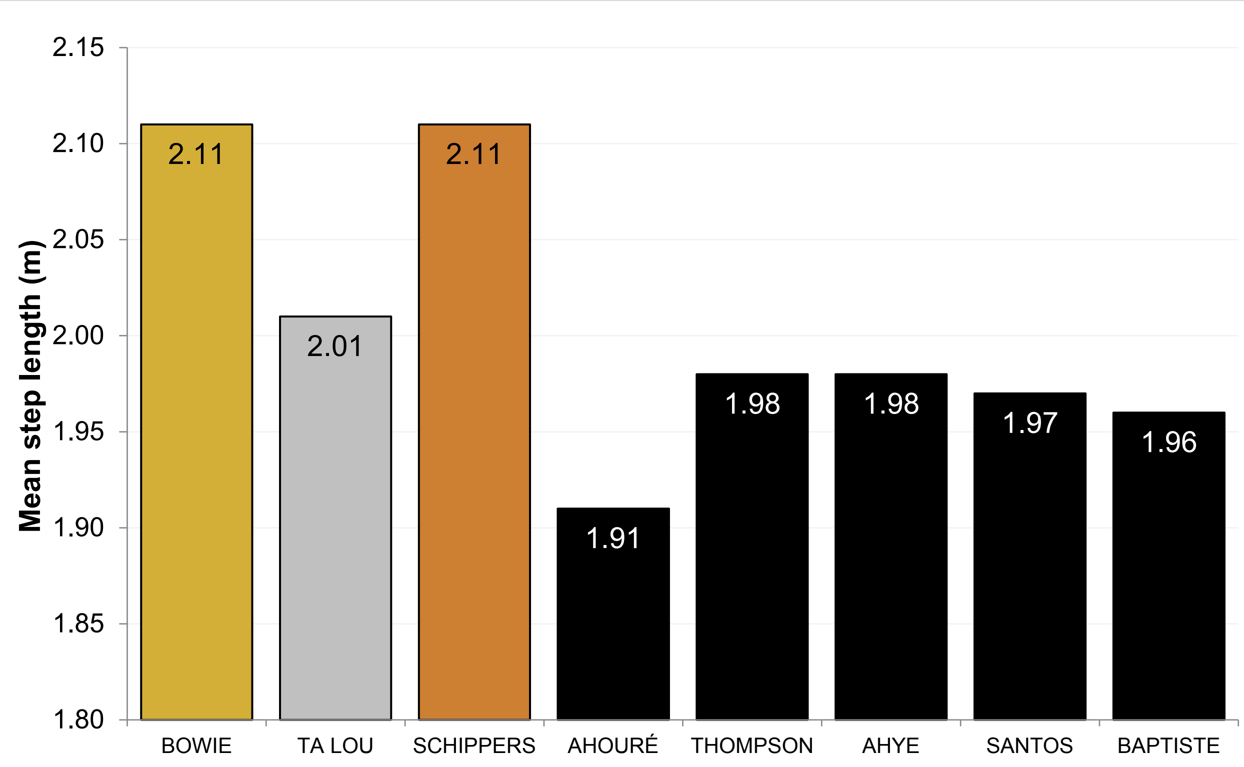

Figure 8. Mean absolute step length for each finalist over 100 metres.

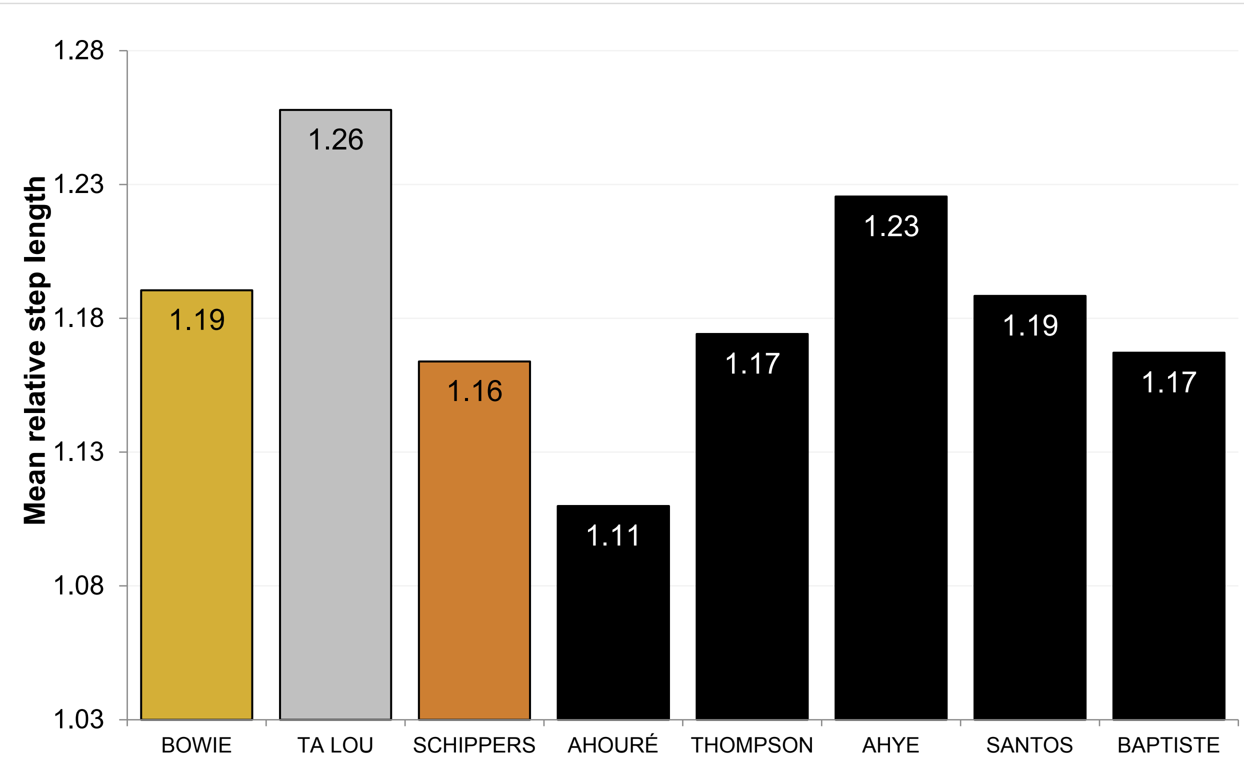

Figure 9. Mean relative step length for each finalist over 100 metres.

Gold medallist profile

TORI BOWIE

Round	*Time*	*vs. SB (22nd June)*	*vs. PB (2016)*	*Notes*
Final	10.85 s	−0.05 s	+0.07 s	New SB

		Final vs. Heat	*Final vs. Semi-final*
Semi-final	10.91 s	-	−0.06 s
Heat	11.05 s	−0.20 s	-

High velocity running phase

The following section of results shows key kinematic characteristics for each finalist during the calibrated volume midway through the race (47-55.5 m). It should be noted that the athletes are likely to still be accelerating at this stage, therefore any left-right differences may not be indicative of a limb asymmetry but a result of an increase in running velocity.

Table 3. Mean step length, relative step length, step rate and step width across two steps for each finalist.

	Step length (m)	Relative step length	Step rate (Hz)	Step width (m)
BOWIE	2.26	1.29	4.72	0.04
TA LOU	2.20	1.38	4.76	0.23
SCHIPPERS	2.30	1.29	4.59	0.09
AHOURÉ	2.07	1.22	4.95	0.18
THOMPSON	2.11	1.27	4.67	0.12
AHYE	2.15	1.35	4.85	0.11
SANTOS	2.18	1.32	4.81	0.17
BAPTISTE	2.11	1.26	5.00	0.19

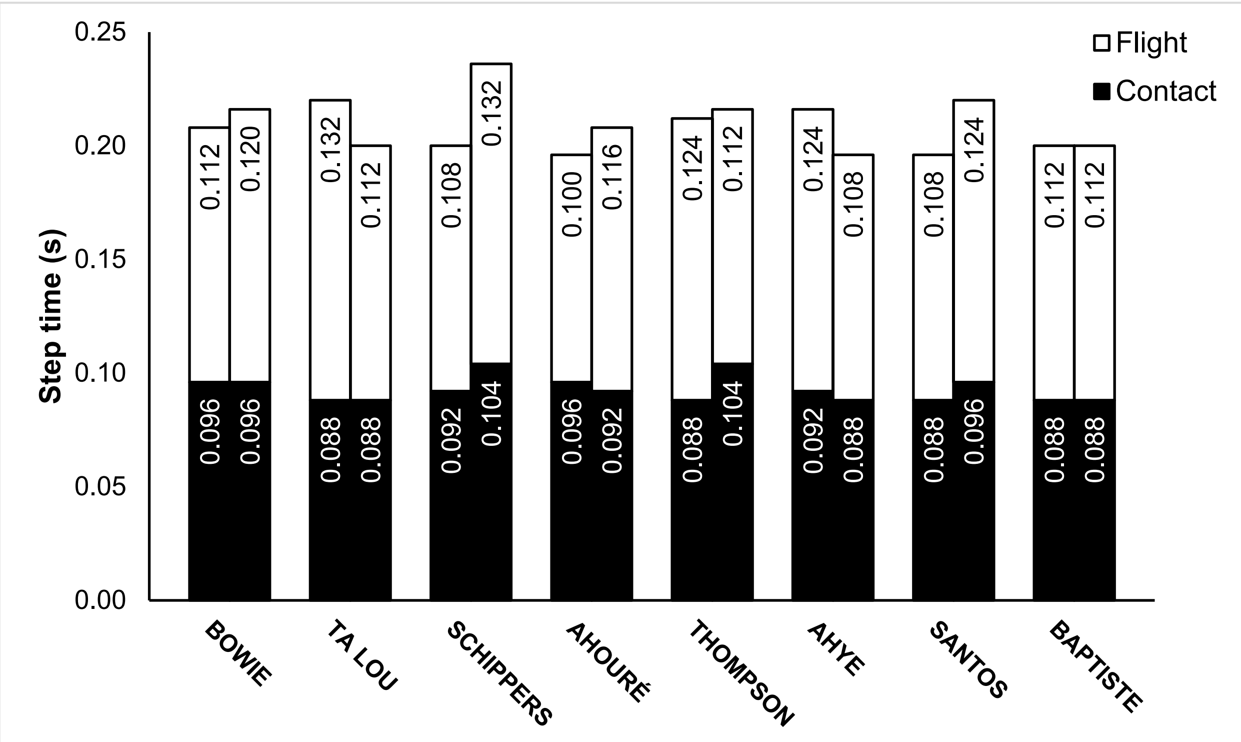

Figure 10. Contact, flight and step times during high velocity running for each finalist. Step time is the sum of contact and flight times. Left and right columns indicate left and right legs for each athlete, respectively.

It should be noted that, at the beginning of the calibrated volume, there was a notable change in Elaine Thompson's running pattern, which appeared to affect her temporal and kinematic characteristics at this stage in the race.

Table 4. Mean running velocity across two steps for each finalist.

	Step velocity (m/s)	CM horizontal velocity (m/s)
BOWIE	10.66	10.61
TA LOU	10.48	10.58
SCHIPPERS	10.55	10.53
AHOURÉ	10.25	10.41
THOMPSON	9.86	10.21
AHYE	10.44	10.42
SANTOS	10.48	10.41
BAPTISTE	10.55	10.43

Note: *Step velocity was calculated using step length and step time, whereas the CM velocity was calculated from the full-body digitised data.*

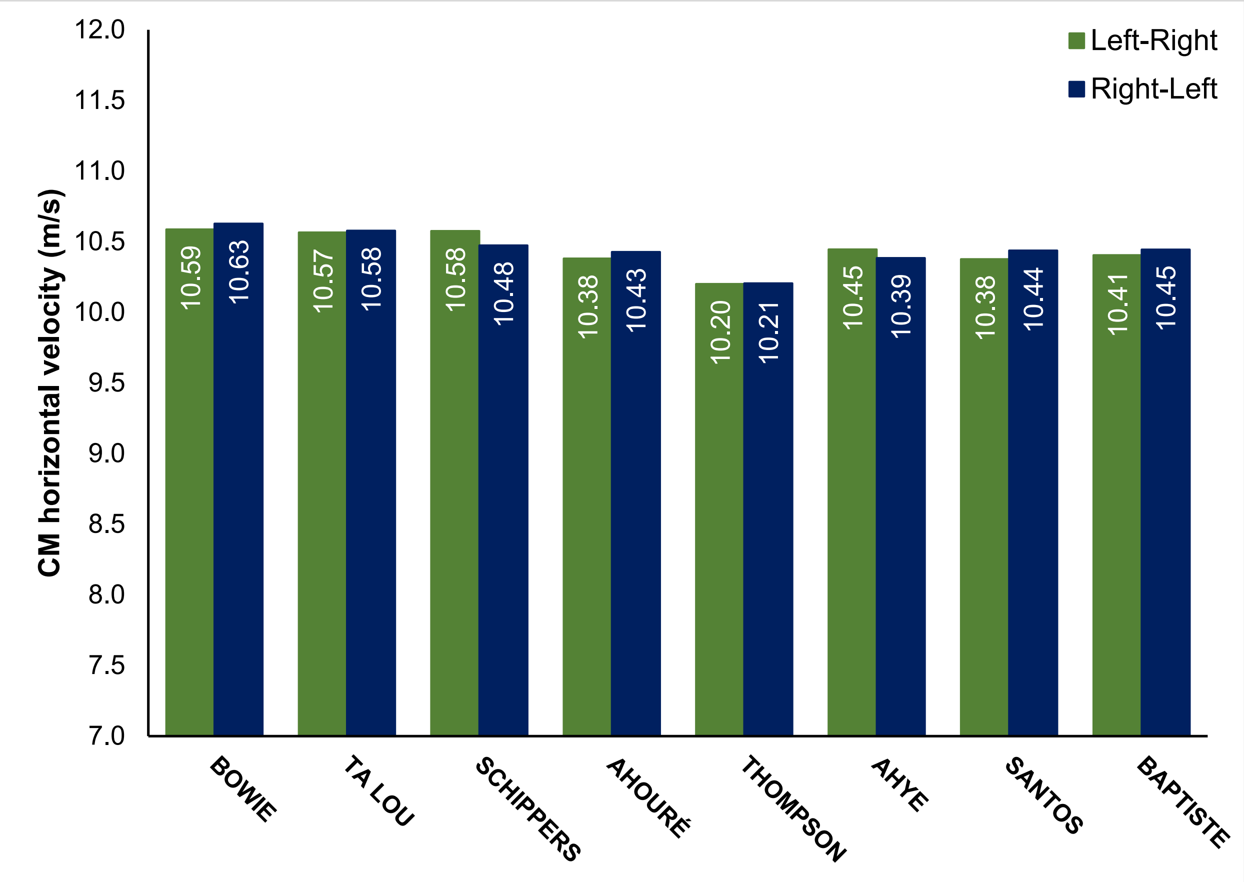

Figure 11. Individual centre of mass horizontal velocities for each digitised step.

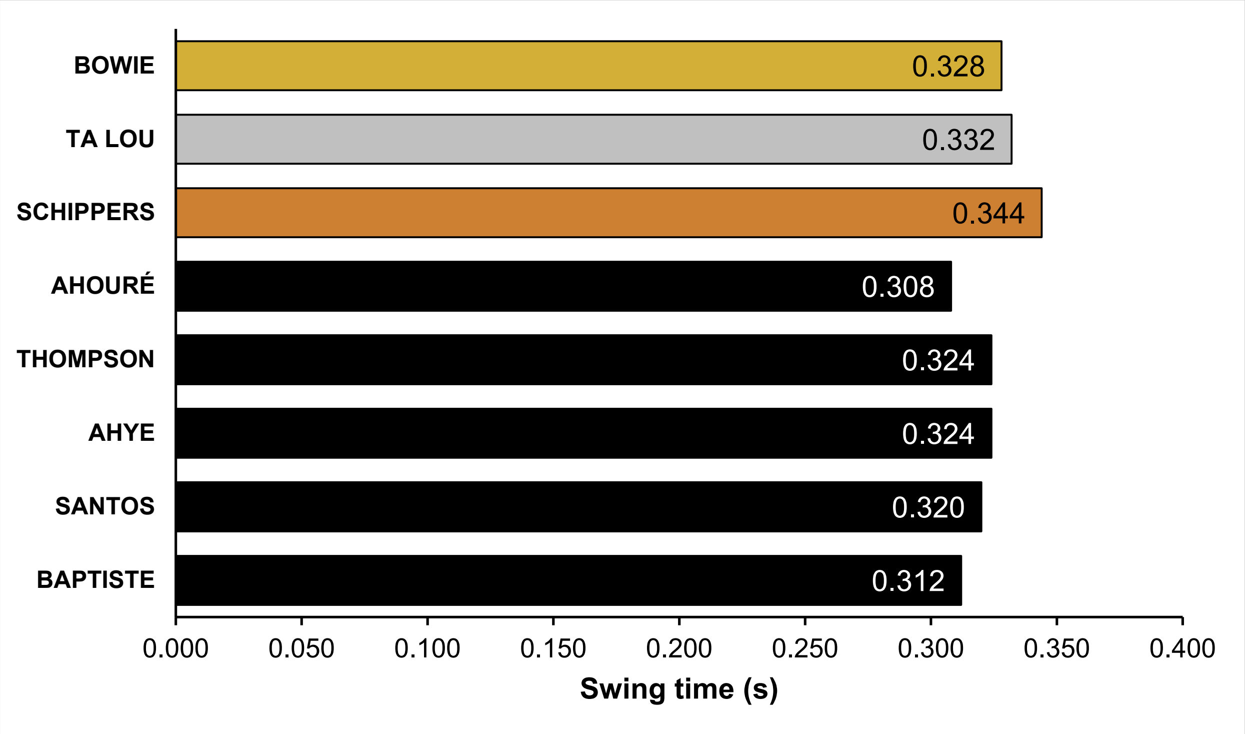

Figure 12. Swing time of one stride for each athlete. For some athletes, the stride was left-left contact, for some it was right-right contact.

Table 5. Horizontal distance from the point of ground contact to the body's CM at both touchdown (DCM TD) and toe-off (DCM TO).

	DCM TD (m / % body height)		DCM TO (m / % body height)	
	Left	Right	Left	Right
BOWIE	0.39 / 22	0.38 / 22	0.58 / 33	0.61 / 35
TA LOU	0.36 / 23	0.29 / 18	0.46 / 29	0.52 / 33
SCHIPPERS	0.32 / 18	0.44 / 24	0.59 / 33	0.52 / 29
AHOURÉ	0.35 / 21	0.39 / 23	0.49 / 29	0.48 / 28
THOMPSON	0.33 / 20	0.45 / 27	0.47 / 28	0.52 / 30
AHYE	0.43 / 27	0.34 / 21	0.47 / 29	0.48 / 30
SANTOS	0.39 / 24	0.36 / 22	0.49 / 29	0.51 / 31
BAPTISTE	0.35 / 21	0.33 / 20	0.48 / 29	0.49 / 29

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

Table 6. Horizontal distance that the CM travelled during ground contact.

	CM contact distance (m / % body height)	
	Left	**Right**
BOWIE	0.97 / 55	0.99 / 57
TA LOU	0.82 / 52	0.81 / 51
SCHIPPERS	0.91 / 51	0.96 / 53
AHOURÉ	0.84 / 50	0.87 / 51
THOMPSON	0.80 /48	0.97 / 57
AHYE	0.90 / 56	0.82 / 51
SANTOS	0.88 / 53	0.87 / 53
BAPTISTE	0.83 / 50	0.82 / 49

Note: *Data are presented as absolute distances and as a percentage of the athlete's heights. Percentage values have been rounded to the nearest integer.*

Figure 13 shows the braking and propulsive portions of the ground contact phase. Values for each athlete are presented for left (upper bar) and right (lower bar) ground contact. 0% of contact time indicates initial touchdown and 100% indicates the final frame before toe-off.

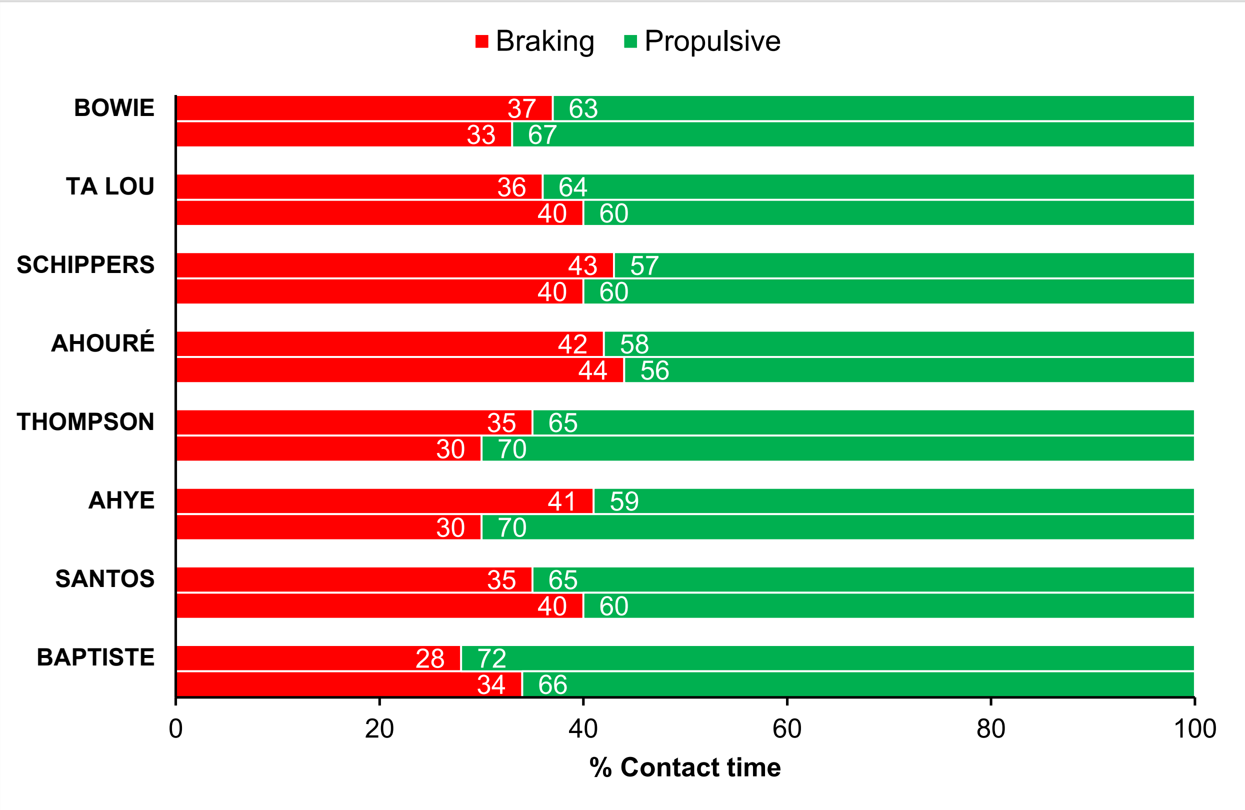

Figure 13. Relative proportions (%) of braking and propulsive phases during contact.

The following eight figures (Figure 14.1 to Figure 14.8) are individual athlete graphs showing the vertical displacement of the centre of mass during left and right contact. Additionally, the vertical velocity of the centre of mass has been plotted on a secondary axis. All data have been normalised from 0 to 100% of ground contact, where 0% represents initial touchdown for both legs and 100% represents toe-off. The vertical lines on each graph indicate the transition point from the braking phase to the propulsive phase, as presented in the chart above (Figure 13).

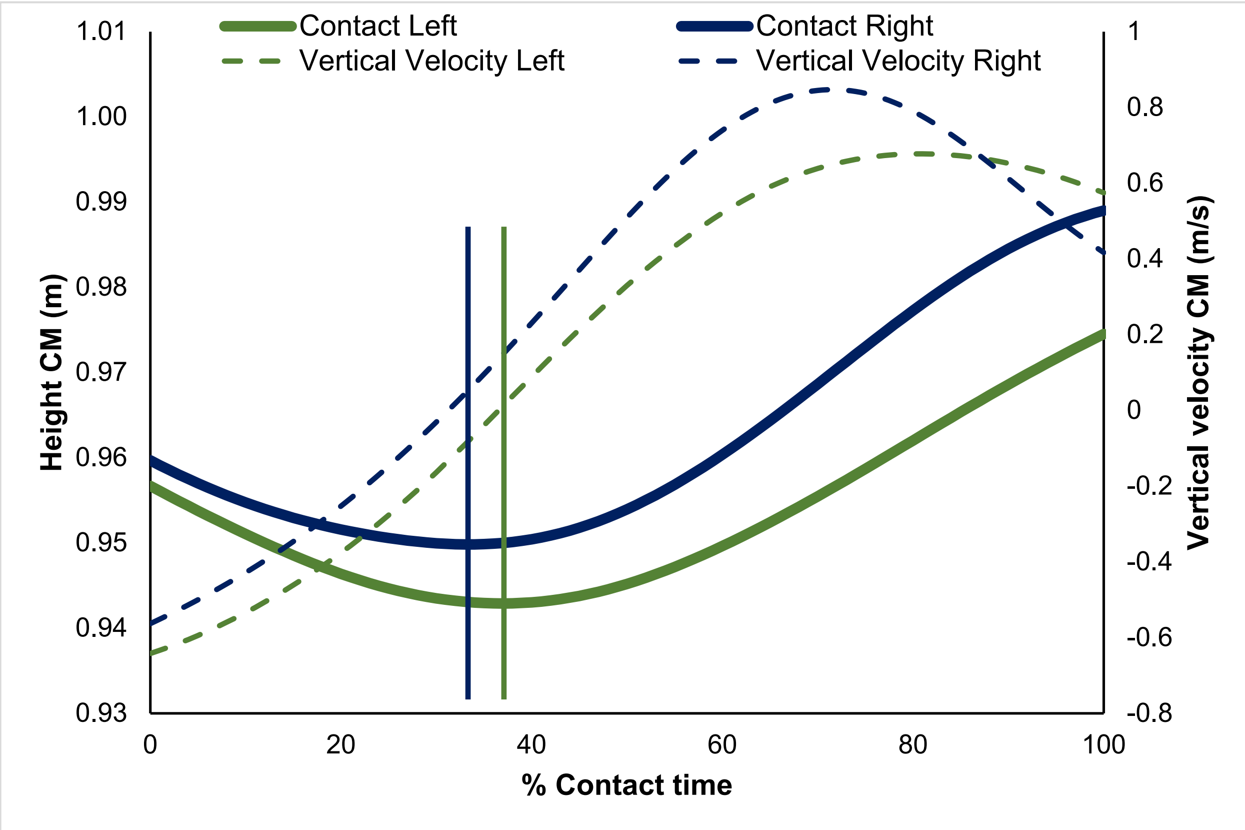

Figure 14.1. CM height and vertical CM velocity during left and right contacts for gold medallist Tori Bowie.

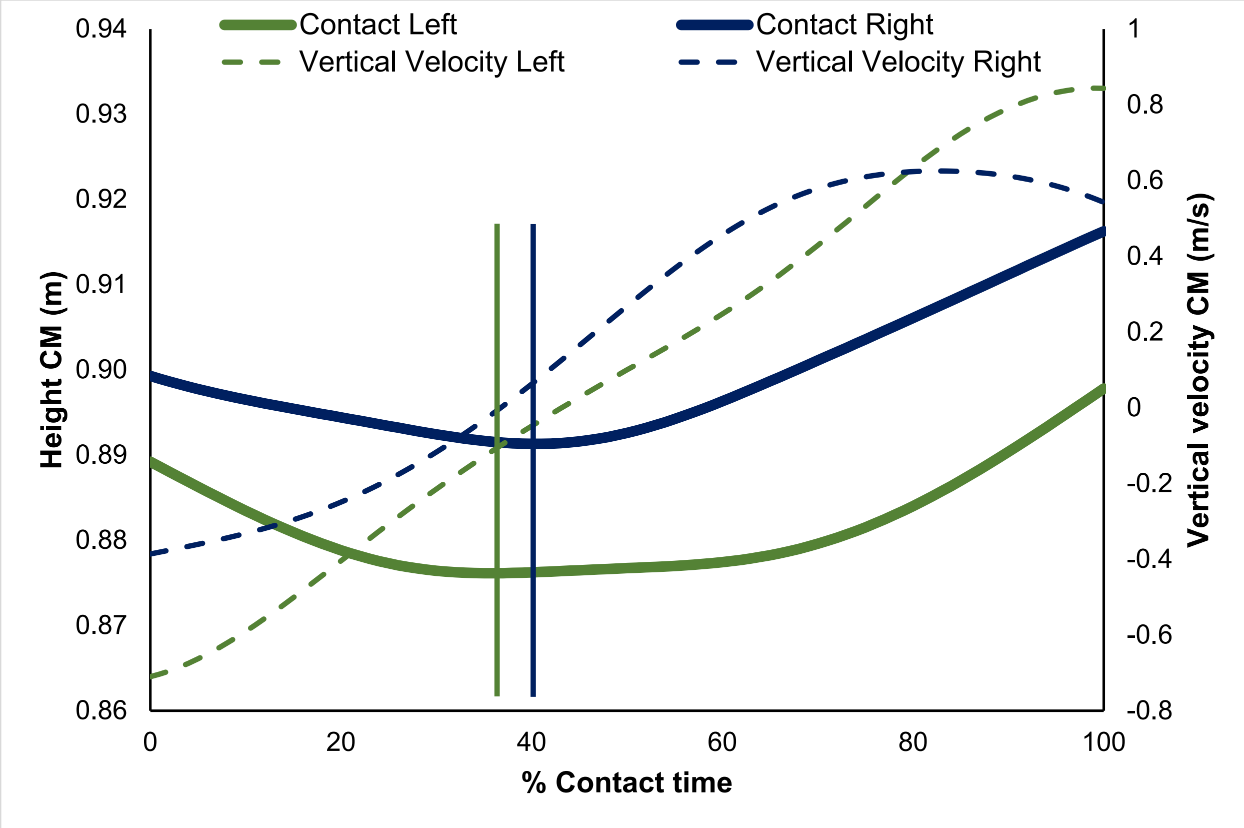

Figure 14.2. CM height and vertical CM velocity during left and right contacts for silver medallist Marie-Josée Ta Lou.

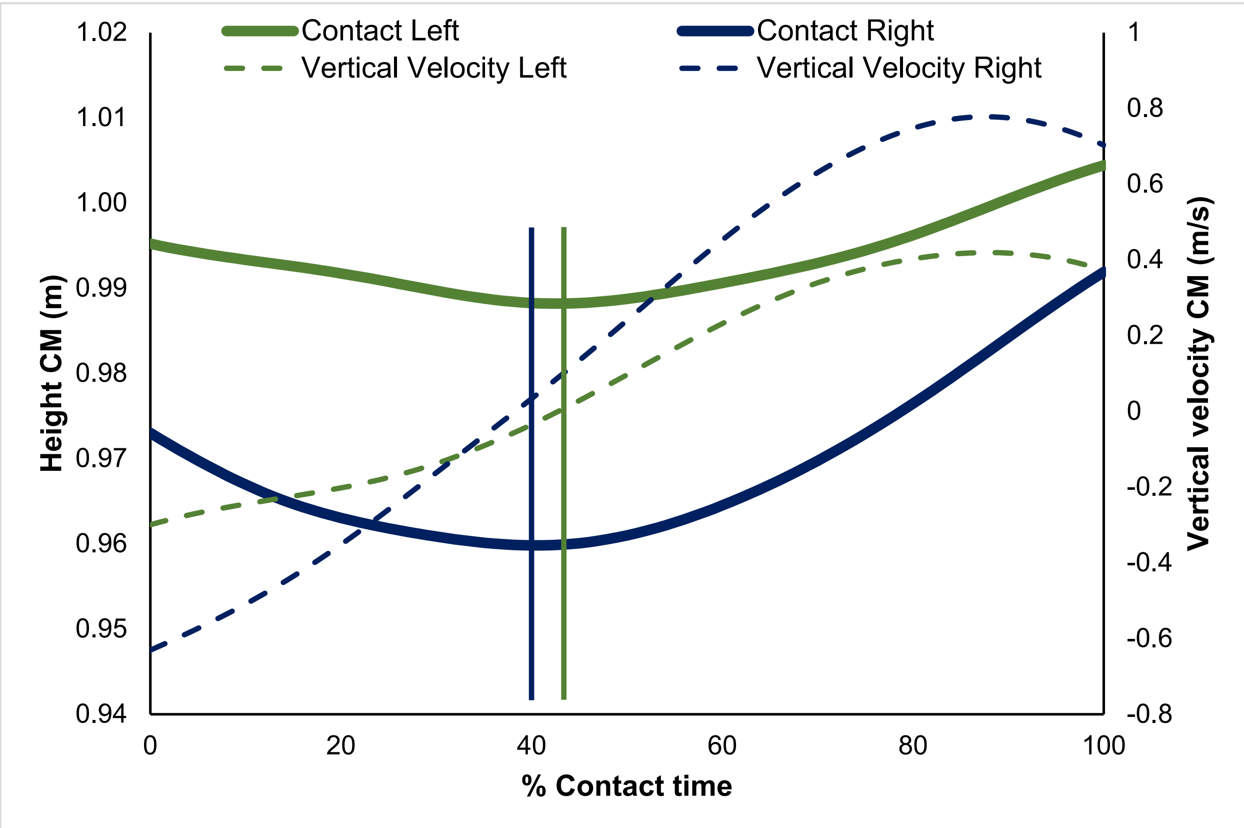

Figure 14.3. CM height and vertical CM velocity during left and right contacts for bronze medallist Dafne Schippers.

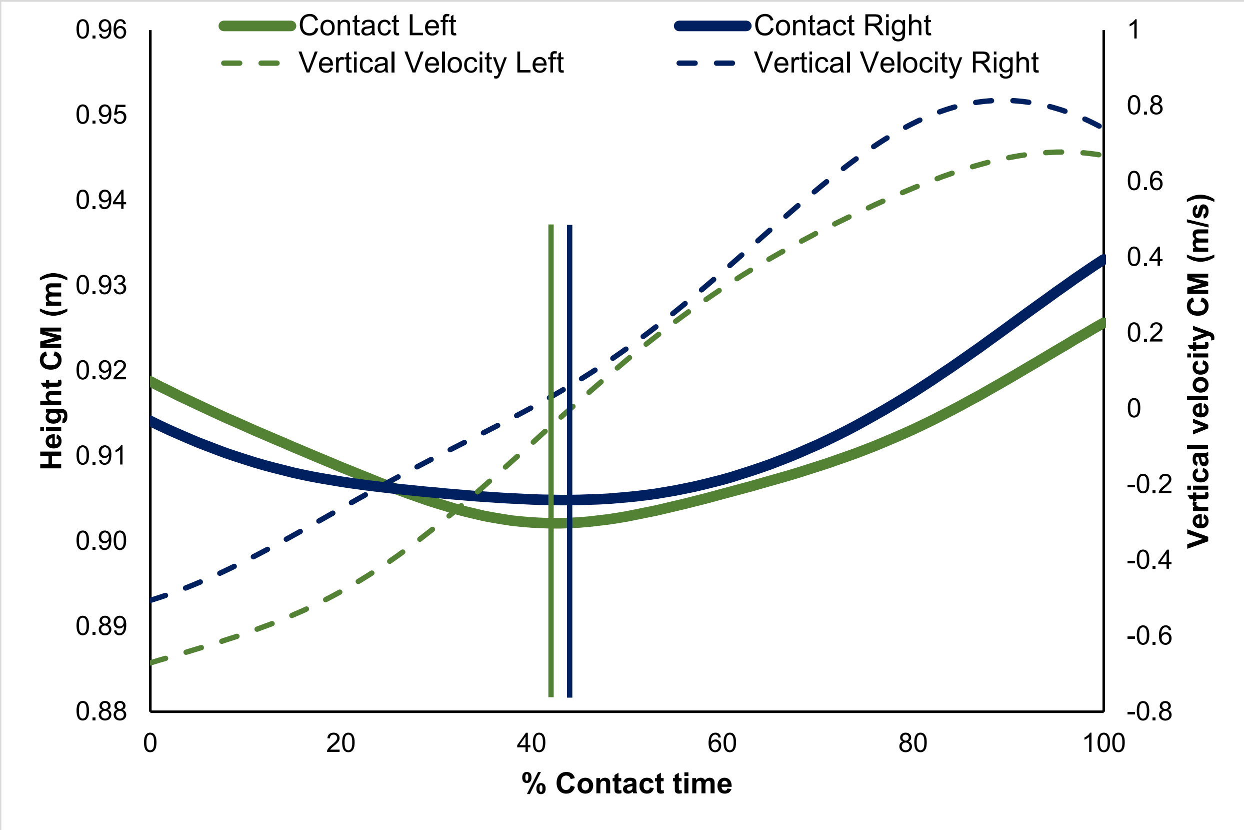

Figure 14.4. CM height and vertical CM velocity during left and right contacts for fourth placed Murielle Ahouré.

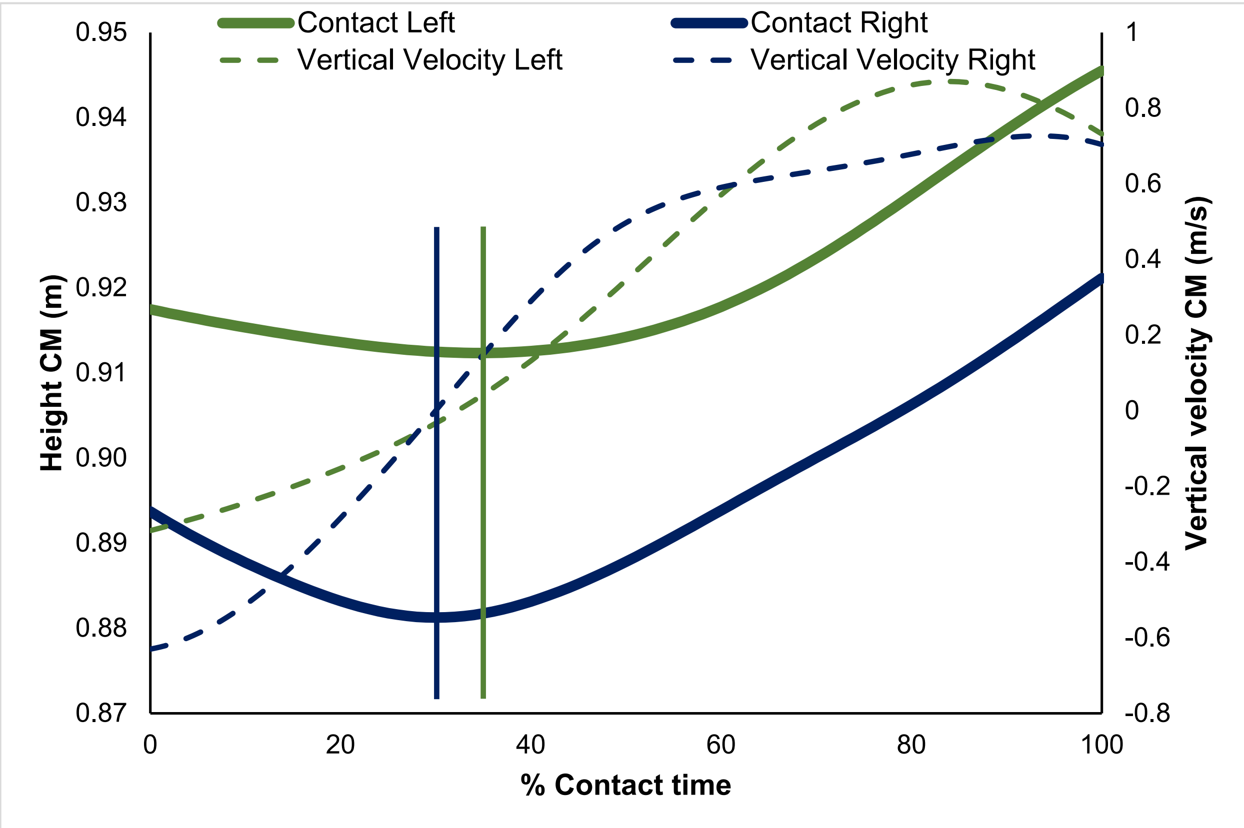

Figure 14.5. CM height and vertical CM velocity during left and right contacts for fifth placed Elaine Thompson.

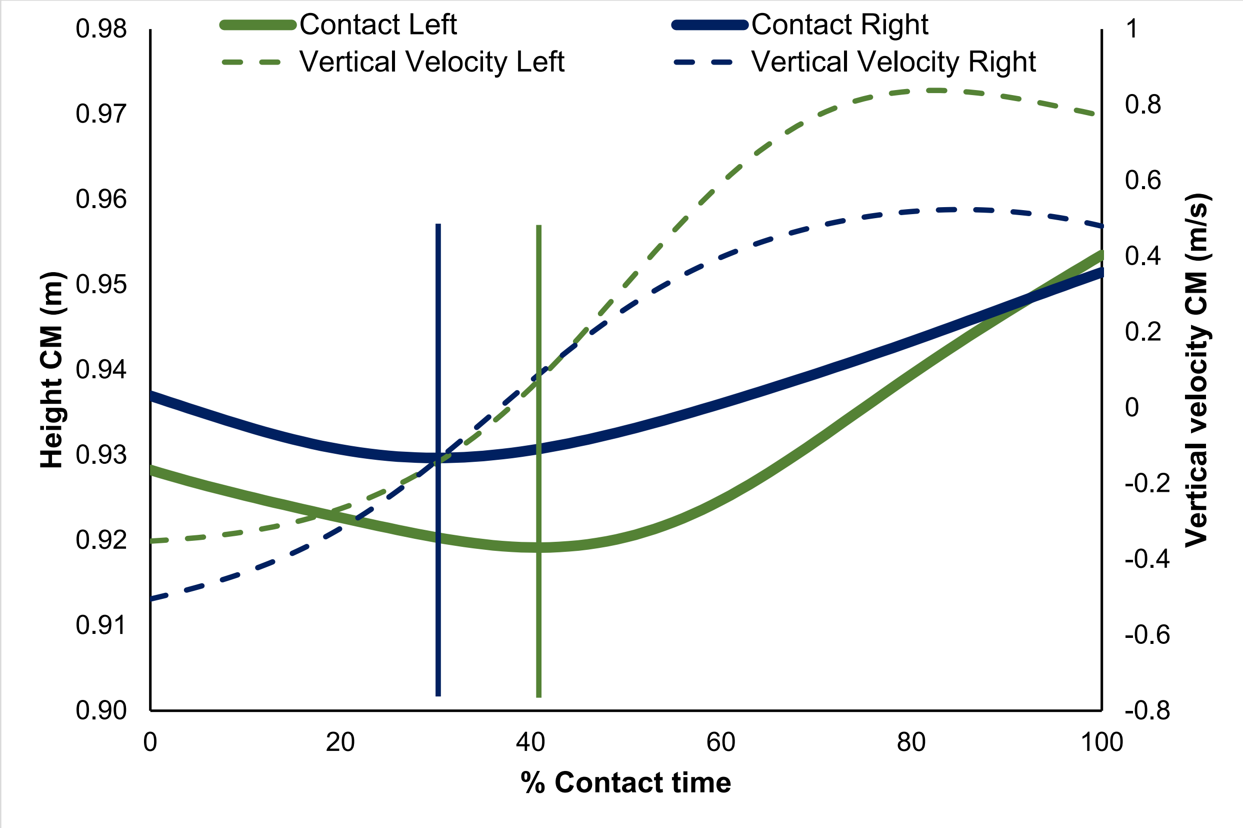

Figure 14.6. CM height and vertical CM velocity during left and right contacts for sixth placed Michelle-Lee Ahye.

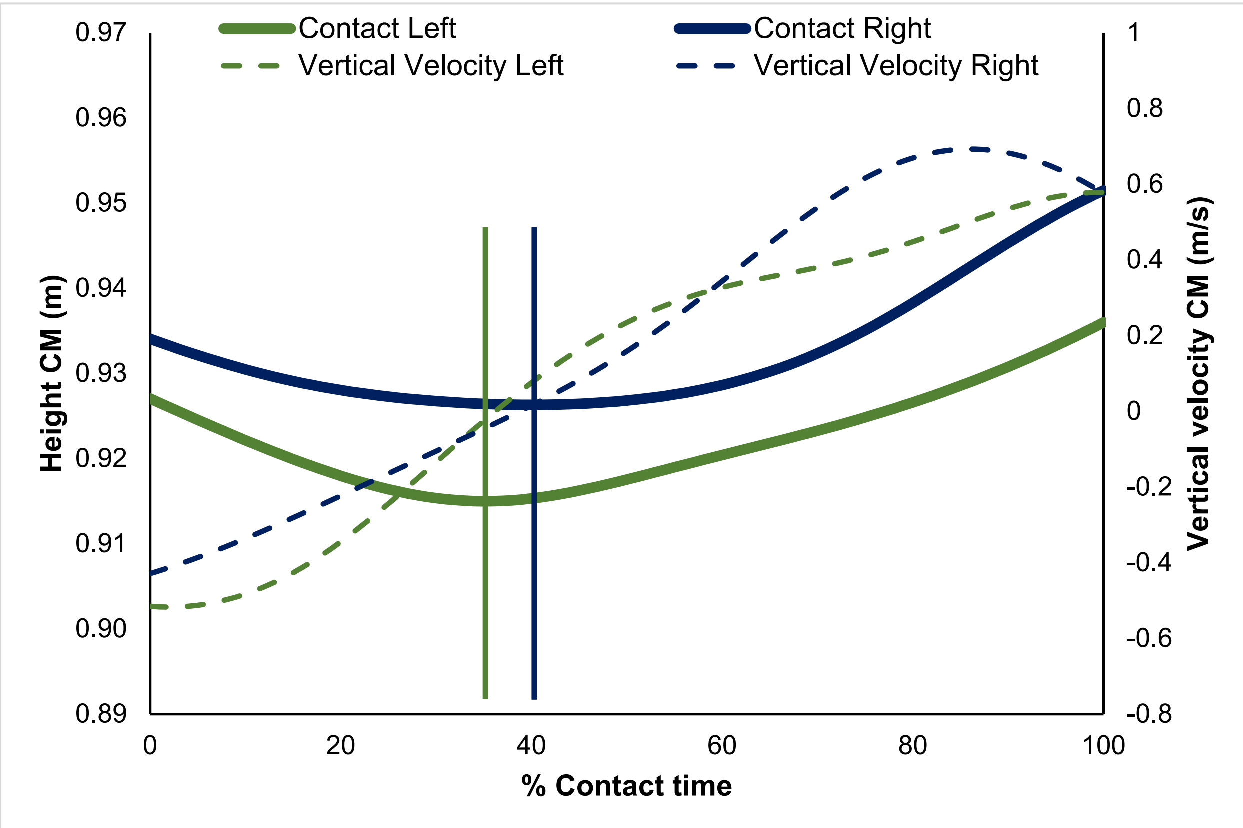

Figure 14.7. CM height and vertical CM velocity during left and right contacts for seventh placed Rosangela Santos.

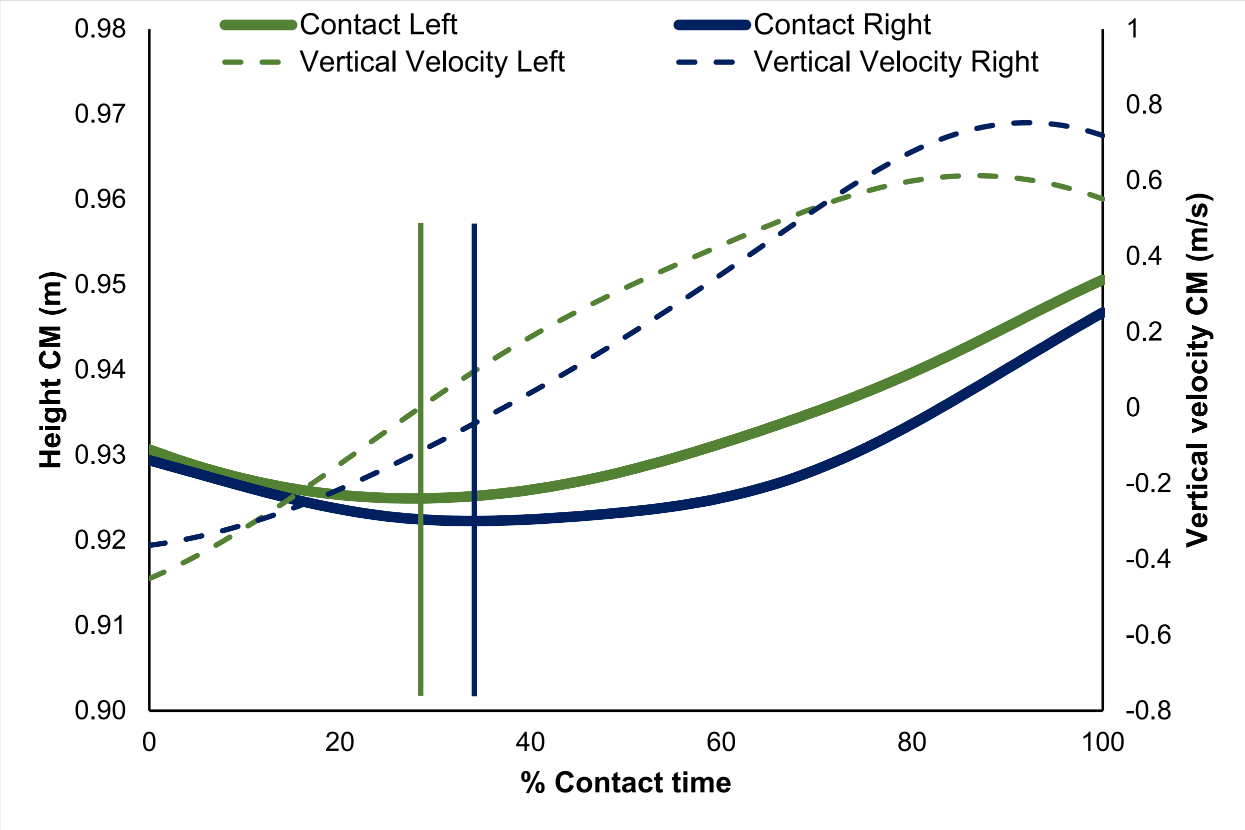

Figure 14.8. CM height and vertical CM velocity during left and right contacts for eighth placed Kelly-Ann Baptiste.

In order to provide a different perspective to touchdown kinematics, the following two tables present horizontal (Table 7) and vertical velocities (Table 8) of each foot of the finalists as they strike the ground during high velocity running.

Table 7. Horizontal velocity of the foot centre of mass at the instant before touchdown and the instant of touchdown. Data presented for left and right feet individually as well as a left-right means at each instant.

	Foot horizontal velocity pre-TD (m/s)		
	Left	**Right**	**Mean**
BOWIE	3.87	2.93	3.40
TA LOU	2.21	2.67	2.44
SCHIPPERS	2.74	3.05	2.90
AHOURÉ	3.72	3.44	3.58
THOMPSON	1.58	3.58	2.58
AHYE	4.25	2.68	3.47
SANTOS	3.56	2.81	3.19
BAPTISTE	1.97	2.33	2.15
	Foot horizontal velocity TD (m/s)		
	Left	**Right**	**Mean**
BOWIE	2.58	1.94	2.26
TA LOU	1.41	1.99	1.70
SCHIPPERS	1.68	1.84	1.76
AHOURÉ	2.69	2.52	2.61
THOMPSON	1.25	2.73	1.99
AHYE	2.71	1.86	2.29
SANTOS	2.52	2.58	2.55
BAPTISTE	1.36	1.63	1.50

Note: *The positive velocities observed indicate that the foot is moving forwards relative to the running surface.*

Table 8. Vertical velocity of the foot centre of mass at the instant before touchdown and the instant of touchdown. Data presented for left and right feet individually as well as a left-right means at each instant.

	Foot vertical velocity pre-TD (m/s)		
	Left	Right	Mean
BOWIE	−2.84	−2.51	−2.68
TA LOU	−3.10	−3.13	−3.12
SCHIPPERS	−3.11	−3.02	−3.07
AHOURÉ	−2.73	−2.85	−2.79
THOMPSON	−3.00	−3.70	−3.35
AHYE	−2.68	−3.36	−3.02
SANTOS	−3.61	−2.98	−3.30
BAPTISTE	−2.64	−2.75	−2.70
	Foot vertical velocity TD (m/s)		
	Left	**Right**	**Mean**
BOWIE	−2.26	−1.90	−2.08
TA LOU	−2.33	−2.59	−2.46
SCHIPPERS	−2.35	−2.25	−2.30
AHOURÉ	−1.99	−2.42	−2.21
THOMPSON	−2.19	−3.10	−2.65
AHYE	−2.17	−2.63	−2.40
SANTOS	−2.90	−2.30	−2.60
BAPTISTE	−1.86	−2.05	−1.96

Note: *The negative velocities observed indicate the downward movement of the foot CM.*

For the swing phase characteristics presented below, it should be noted that the swing phase has been broken into two distinct phases: the ‘recovery’ phase and the ‘driving’ phase. The ‘recovery’ phase has been defined as the time between toe-off and the point where the knee joint is beneath the whole-body CM. The ‘driving’ phase has been defined from the point where the knee passes beneath the whole-body CM until touchdown of the ipsilateral leg. All % values seen in Table 9 and Figure 15 are displayed as a percentage of swing time, where 0% represents the first frame of toe-off and 100% represents touchdown of the ipsilateral leg.

Table 9. Peak resultant velocity of the foot CM during the swing phase and time of transition for one stride.

	Resultant foot swing velocity (m/s)				
	Recovery	% swing	Transition (%)	Driving	% swing
BOWIE	16.21	23	35	19.05	66
TA LOU	16.79	31	37	19.61	65
SCHIPPERS	16.26	28	30	17.99	62
AHOURÉ	17.46	27	27	19.38	66
THOMPSON	16.30	32	32	18.82	61
AHYE	15.84	27	38	19.43	67
SANTOS	15.12	30	32	17.84	63
BAPTISTE	16.91	28	31	19.51	62

Note: *As only one stride was fully digitised, the foot swing velocities presented here are of the left foot for some athletes and the right foot for others.*

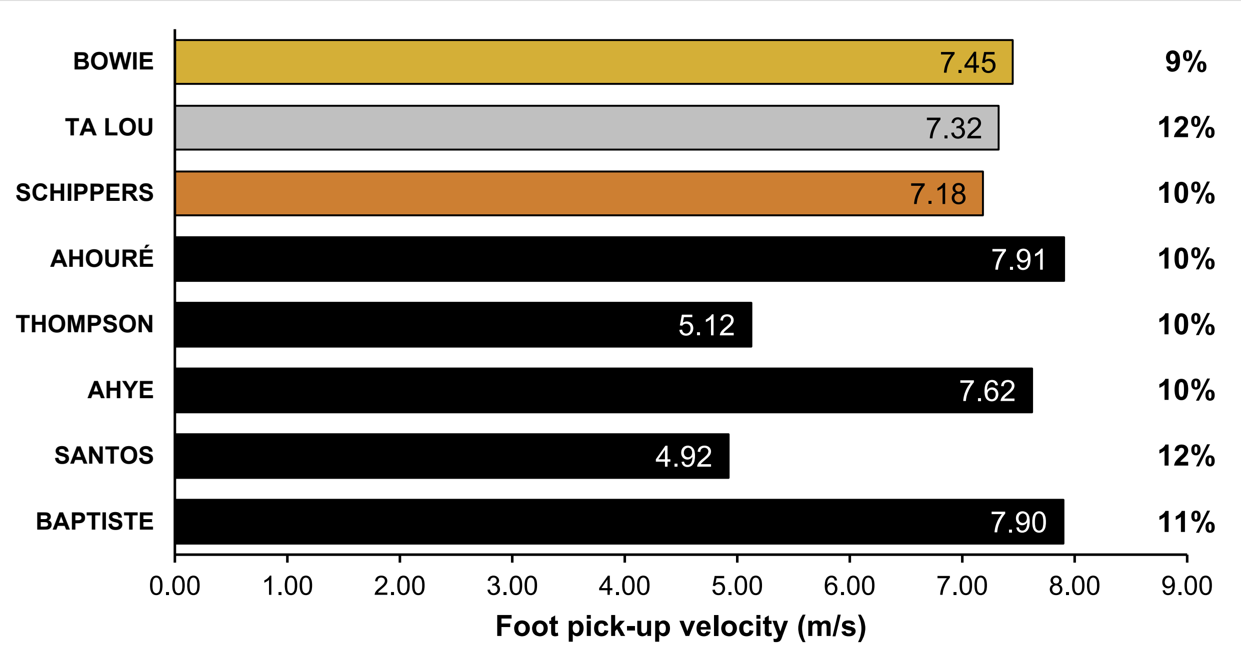

Figure 15. The peak vertical velocity of the foot CM during the swing phase. For all athletes, this peak value occurred shortly after toe-off and has been termed 'foot pick-up velocity'.

The following page consists of two graphs. The graphs contain the time-series data for the resultant velocity of the foot CM, displayed as a percentage of swing time. The vertical lines seen on Figure 16.1 indicate the phase transition from 'recovery' to 'driving', as described above and shown in Table 9, for each of the medallists. As is the case for Table 9, the swing velocities for some athletes have been calculated from the left leg, whereas the right leg was used for some others.

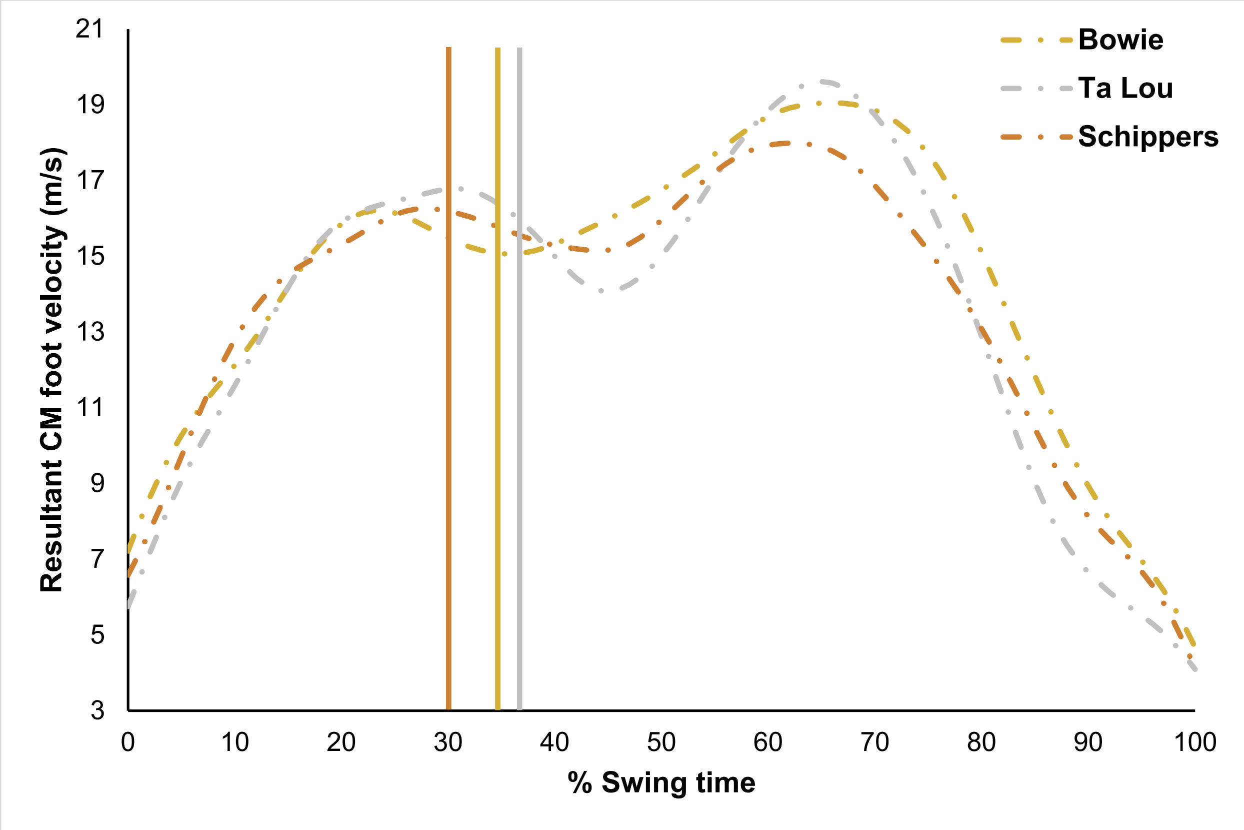

Figure 16.1. Resultant foot CM velocity during the swing phase for the three medallists, displayed as a percentage of swing time.

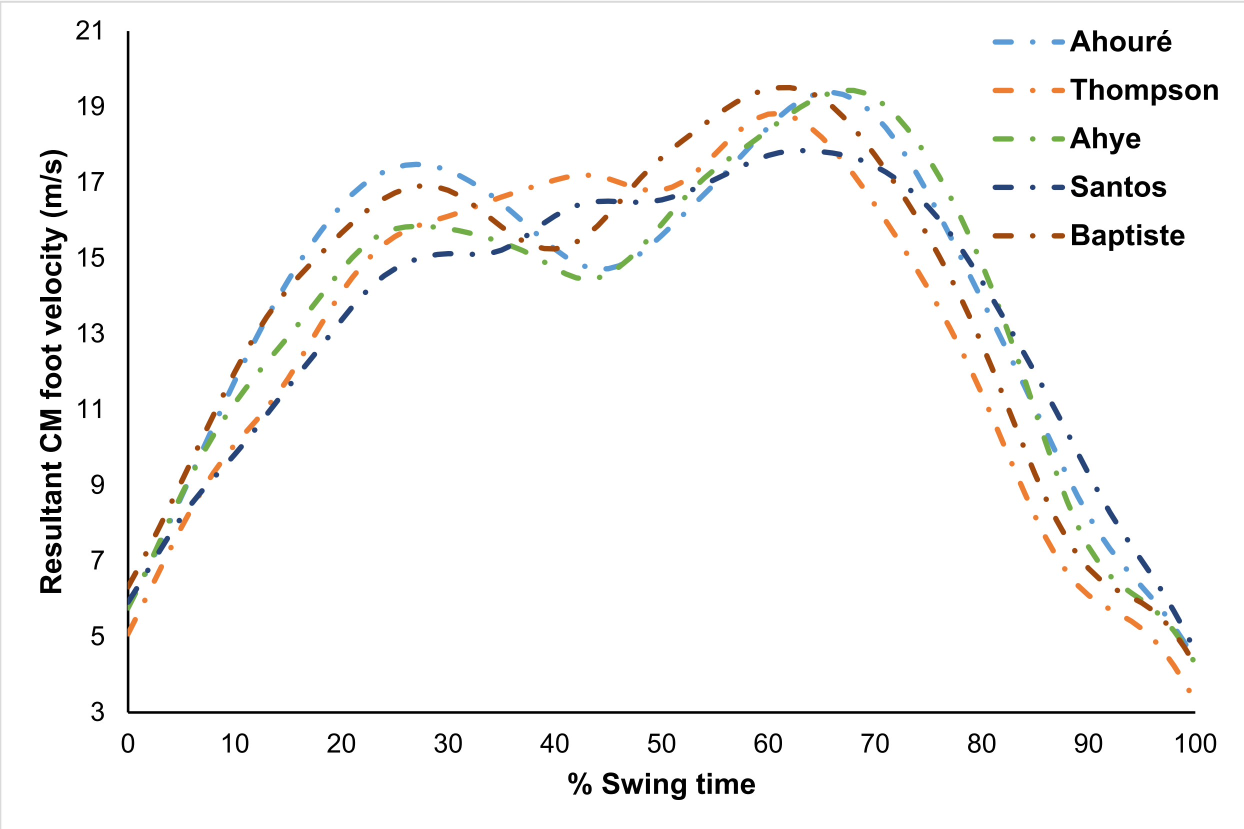

Figure 16.2. Resultant foot CM velocity during the swing phase for the remaining finalists, displayed as a percentage of swing time.

The following section describes key joint angles for the critical instants of touchdown and toe-off with Figures 17 and 18 providing visual depictions of these angles.

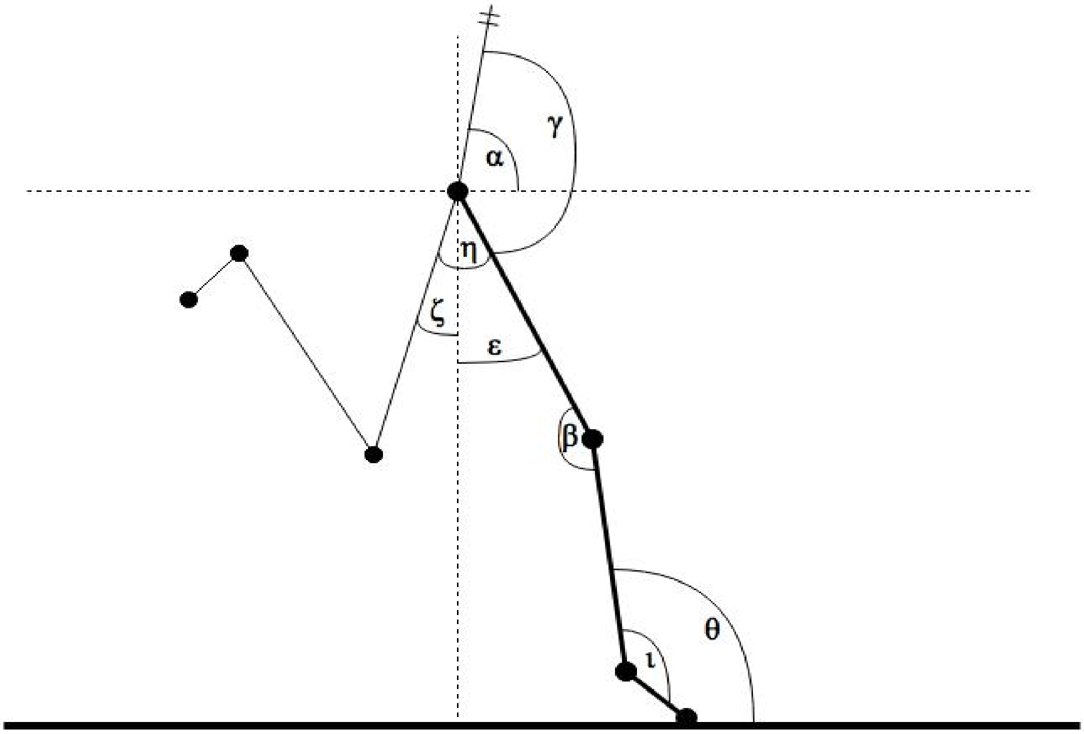

Figure 17. Body schematic denoting angles measured at touchdown. This does not represent any athlete's posture but is merely for illustration purposes.

Table 10. Joint angles at touchdown for the three medallists.

	BOWIE		TA LOU		SCHIPPERS	
	Left (°)	Right (°)	Left (°)	Right (°)	Left (°)	Right (°)
α	77.6	81.2	80.0	76.1	77.1	78.4
β	150.9	145.5	156.5	159.7	155.4	150.7
γ	139.8	144.3	147.4	141.1	143.7	139.4
ε	33.0	31.9	27.1	26.2	26.9	35.4
ζ	9.5	−2.1	2.5	11.8	27.9	14.5
η	−23.5	−34.0	−24.6	−14.4	1.0	−20.9
θ	96.7	97.9	94.1	96.0	95.5	98.0
ι	118.7	108.8	114.0	122.6	120.4	118.9

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.*

Table 11. Joint angles at touchdown for the remaining five finalists.

	AHOURÉ		THOMPSON		AHYE	
	Left (°)	Right (°)	Left (°)	Right (°)	Left (°)	Right (°)
α	86.9	84.2	77.8	76.1	88.4	84.2
β	161.7	150.4	154.2	148.8	166.8	143.5
γ	149.5	145.3	139.2	135.4	129.0	133.0
ε	24.0	33.8	30.4	38.5	27.8	34.2
ζ	1.8	1.4	14.8	6.0	−2.1	15.9
η	−22.2	−32.4	−15.6	−32.5	−29.9	−18.3
θ	100.7	94.6	96.4	102.4	108.1	97.9
ι	119.4	122.3	125.0	115.2	126.5	111.6

	SANTOS		BAPTISTE	
	Left (°)	Right (°)	Left (°)	Right (°)
α	71.1	73.9	78.2	77.8
β	159.8	152.9	166.6	156.4
γ	136.6	136.1	154.4	145.6
ε	28.9	31.1	20.6	25.1
ζ	25.0	13.2	21.5	25.4
η	−3.9	−17.9	0.9	0.3
θ	103.5	95.1	100.0	93.6
ι	122.2	116.3	119.1	112.7

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.*

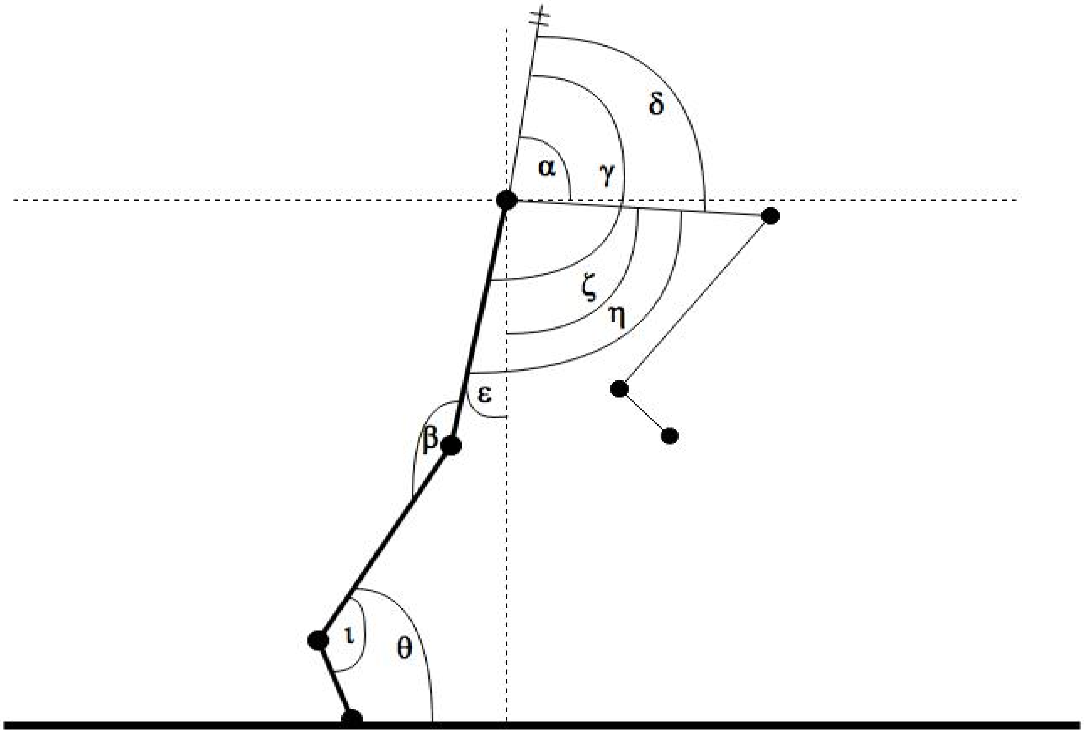

Figure 18. Body schematic denoting joint angles measured at toe-off. This does not represent any athlete's posture but is merely for illustration purposes.

Table 12. Joint angles at toe-off for the three medallists.

	BOWIE		TA LOU		SCHIPPERS	
	Left (°)	Right (°)	Left (°)	Right (°)	Left (°)	Right (°)
α	86.3	87.4	86.6	83.9	85.4	83.9
β	169.0	157.4	137.0	146.4	147.4	153.0
γ	211.3	207.1	202.2	195.1	199.6	206.7
δ	117.5	119.1	112.3	118.3	104.3	114.1
ε	−37.5	−31.2	−10.7	−21.5	−26.7	−21.8
ζ	61.0	62.0	61.1	68.4	73.5	68.4
η	98.5	93.2	71.8	89.9	100.2	90.2
θ	42.1	36.4	37.8	36.0	40.6	41.4
ι	137.3	128.3	128.9	116.0	145.2	131.4

***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 in the sagittal plane 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 13. Joint angles at toe-off for the remaining five finalists.

	AHOURÉ		THOMPSON		AHYE	
	Left (°)	**Right (°)**	**Left (°)**	**Right (°)**	**Left (°)**	**Right (°)**
α	86.0	84.3	80.5	79.2	85.0	87.1
β	163.6	158.9	148.8	150.7	144.1	149.7
γ	205.5	203.7	186.0	187.6	204.8	193.8
δ	111.4	119.4	109.1	106.9	113.3	98.9
ε	−32.8	−27.4	−17.1	−21.5	−16.2	−20.1
ζ	65.5	62.4	64.6	66.4	58.1	65.6
η	98.3	89.8	81.7	87.9	113.3	85.7
θ	42.9	41.7	41.7	39.0	38.4	40.0
ι	128.3	121.5	132.7	130.2	134.0	127.1

	SANTOS		BAPTISTE	
	Left (°)	**Right (°)**	**Left (°)**	**Right (°)**
α	83.3	79.3	81.3	81.3
β	136.3	147.7	155.8	158.7
γ	195.0	186.5	196.5	191.7
δ	108.3	109.4	105.3	105.5
ε	−13.8	−17.0	−24.6	−25.2
ζ	64.6	66.2	65.8	71.3
η	78.4	83.2	90.4	96.5
θ	32.8	40.7	41.5	43.7
ι	136.7	142.5	127.0	129.4

***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 in the sagittal plane 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.*

Tables 14 and 15 shows the minimum knee (**β**) and ankle (**ι**) joint angles during left and right contact, as well as the absolute change in joint angle from touchdown to the minimum value.

Table 14. Minimum knee joint angles and change in knee angle from touchdown to minimum knee angle during left and right contacts for each finalist.

	Minimum knee angle (°)		Δ knee angle (°)	
	Left	Right	Left	Right
BOWIE	139.9	134.6	11.0	10.9
TA LOU	129.7	134.5	26.8	25.2
SCHIPPERS	144.5	129.9	10.9	20.8
AHOURÉ	144.5	141.1	17.2	9.3
THOMPSON	138.7	126.0	15.5	22.8
AHYE	135.8	141.7	31.0	1.8
SANTOS	131.7	142.6	28.1	10.3
BAPTISTE	152.6	144.3	14.0	12.1

Note: *Knee angles shown here are represented by angle 'β' in Figure 17.*

Table 15. Minimum ankle joint angles and change in ankle angle from touchdown to minimum ankle angle during left and right contacts for each finalist.

	Minimum ankle angle (°)		Δ ankle angle (°)	
	Left	Right	Left	Right
BOWIE	89.3	84.4	29.4	24.4
TA LOU	95.4	88.5	18.6	34.1
SCHIPPERS	89.5	85.8	30.9	33.1
AHOURÉ	88.4	92.8	31.0	29.5
THOMPSON	101.0	80.8	24.0	34.4
AHYE	92.6	86.9	33.9	24.7
SANTOS	87.8	88.2	34.4	28.1
BAPTISTE	89.1	85.9	30.0	26.8

Note: *Ankle angles shown here are represented by angle 'ι' in Figure 17.*

The following four pages display angular velocity graphs for each individual athlete. Angular velocities have been calculated for the hip, knee and ankle joints across a full stride, i.e., from touchdown to the next ipsilateral touchdown (left-left or right-right). Therefore, the graphs display the data as a percentage of stride time, where 0% and 100% represent the two touchdowns of the same leg. Positive angular velocity values indicate hip extension, knee extension and ankle plantarflexion (indicated by "*Extension*"), whereas negative angular velocity values indicate hip flexion, knee flexion and ankle dorsiflexion (indicated by "*Flexion*").

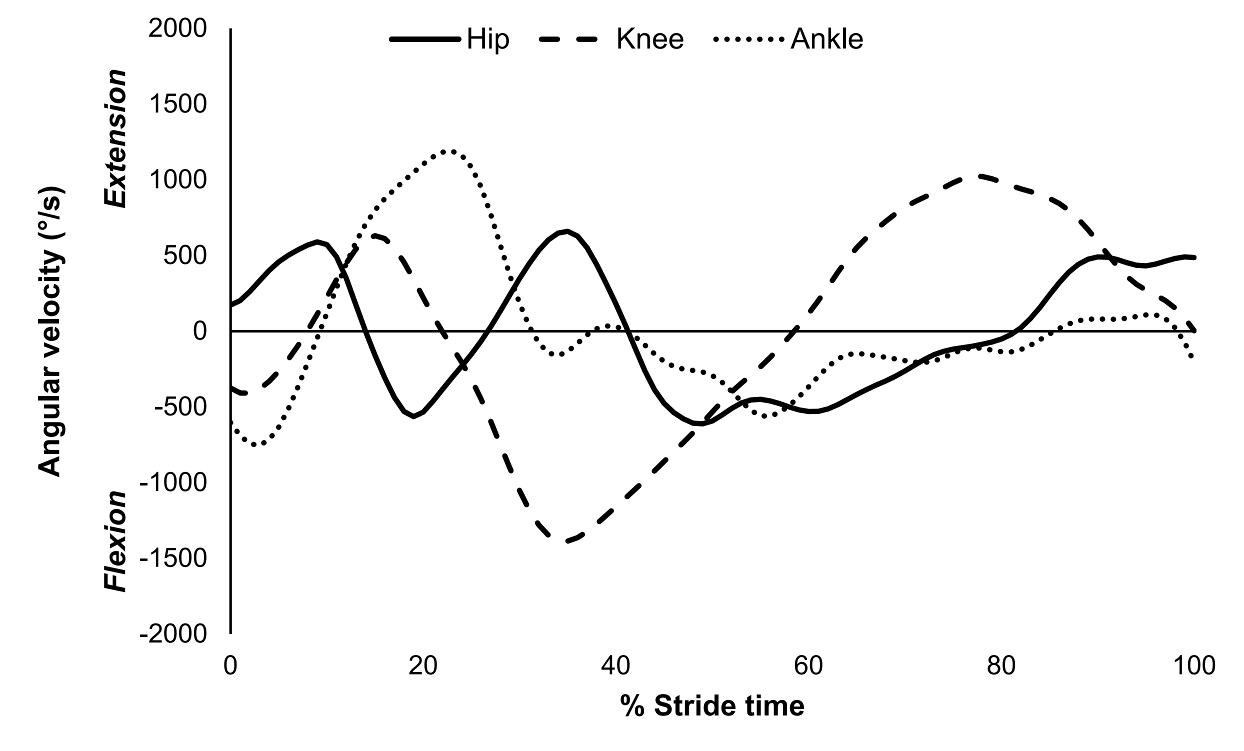

Figure 19.1. Hip, knee and ankle angular velocity over one stride for gold medallist Tori Bowie.

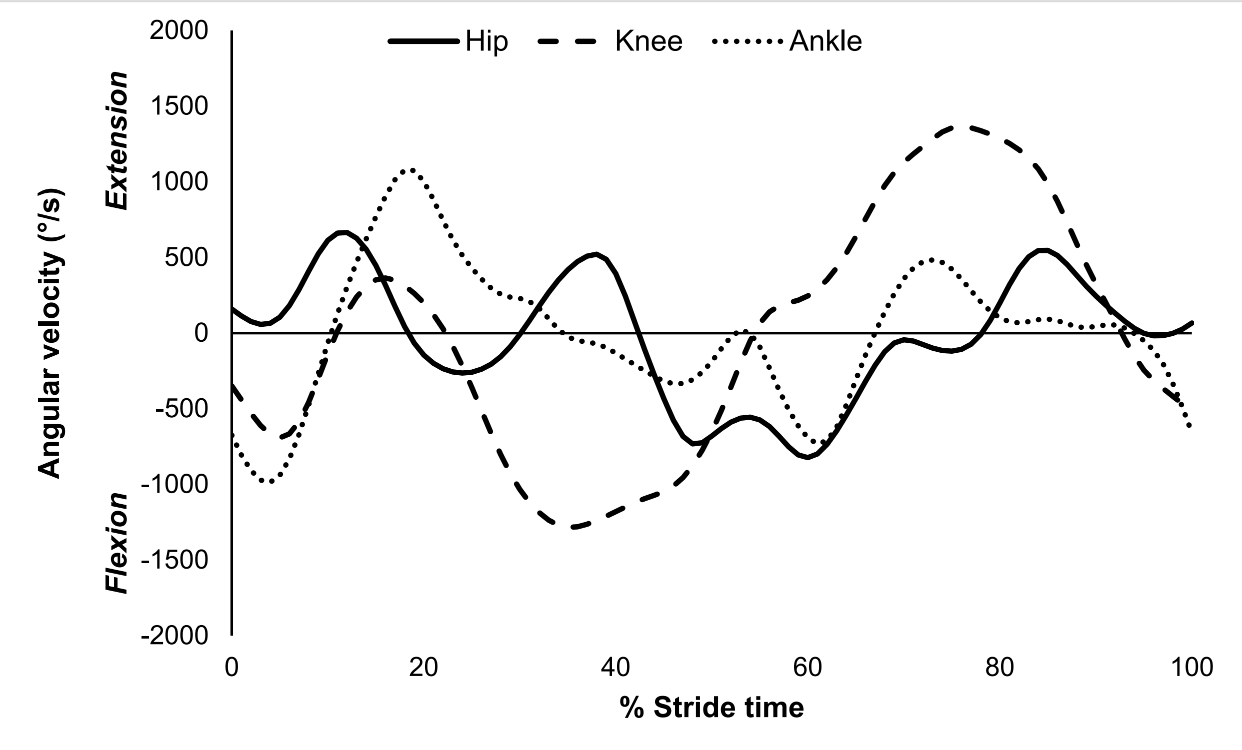

Figure 19.2. Hip, knee and ankle angular velocity over one stride for silver medallist Marie-Josée Ta Lou.

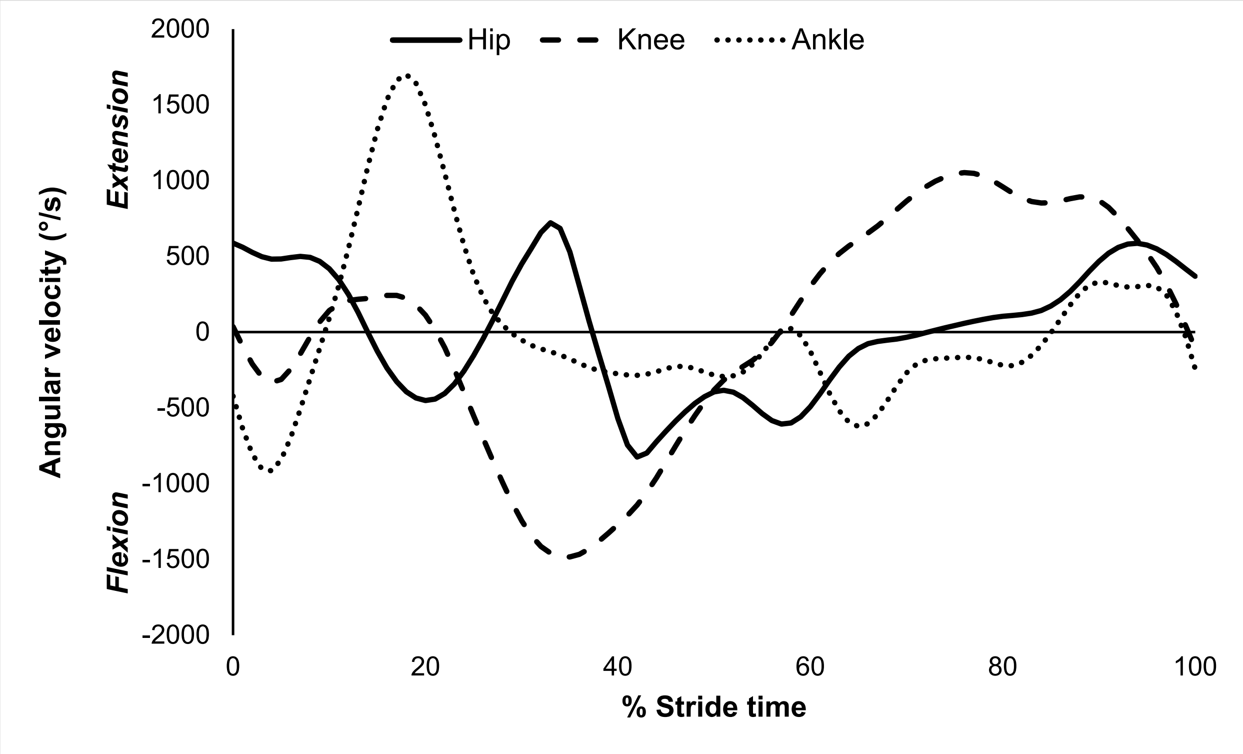

Figure 19.3. Hip, knee and ankle angular velocities over one stride for bronze medallist Dafne Schippers.

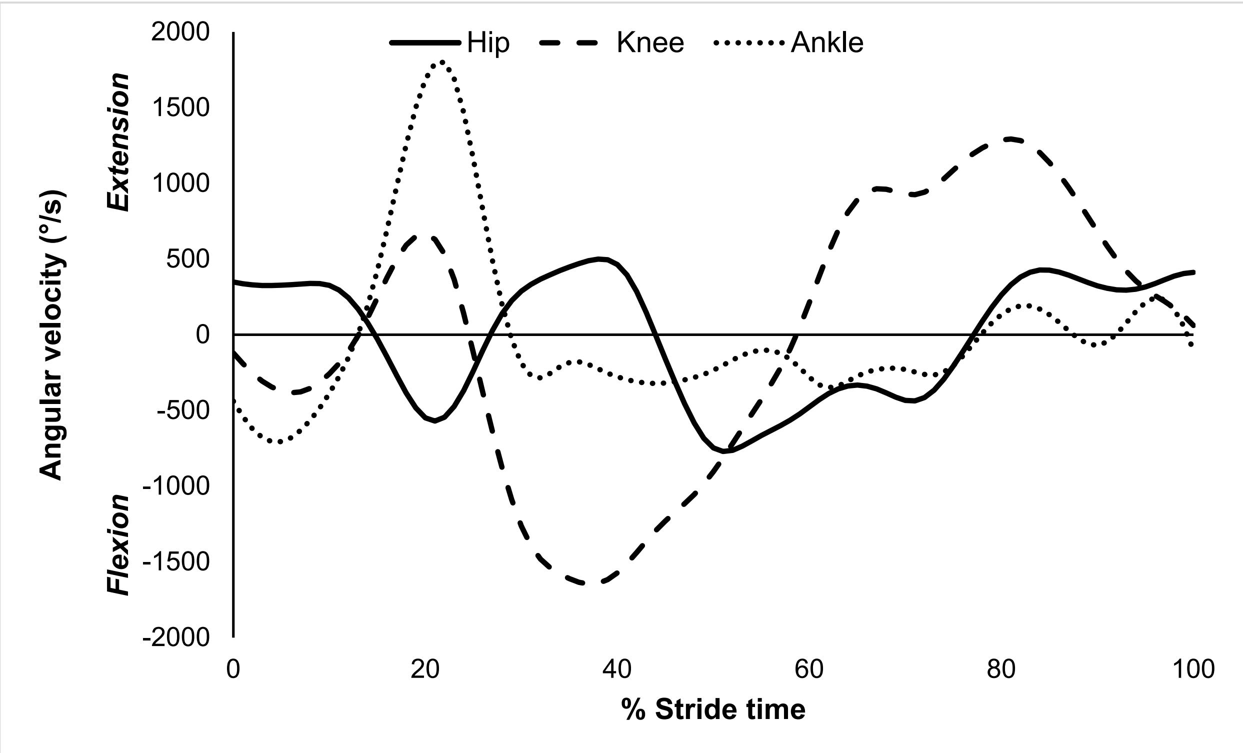

Figure 19.4. Hip, knee and ankle angular velocities over one stride for fourth placed Murielle Ahouré.

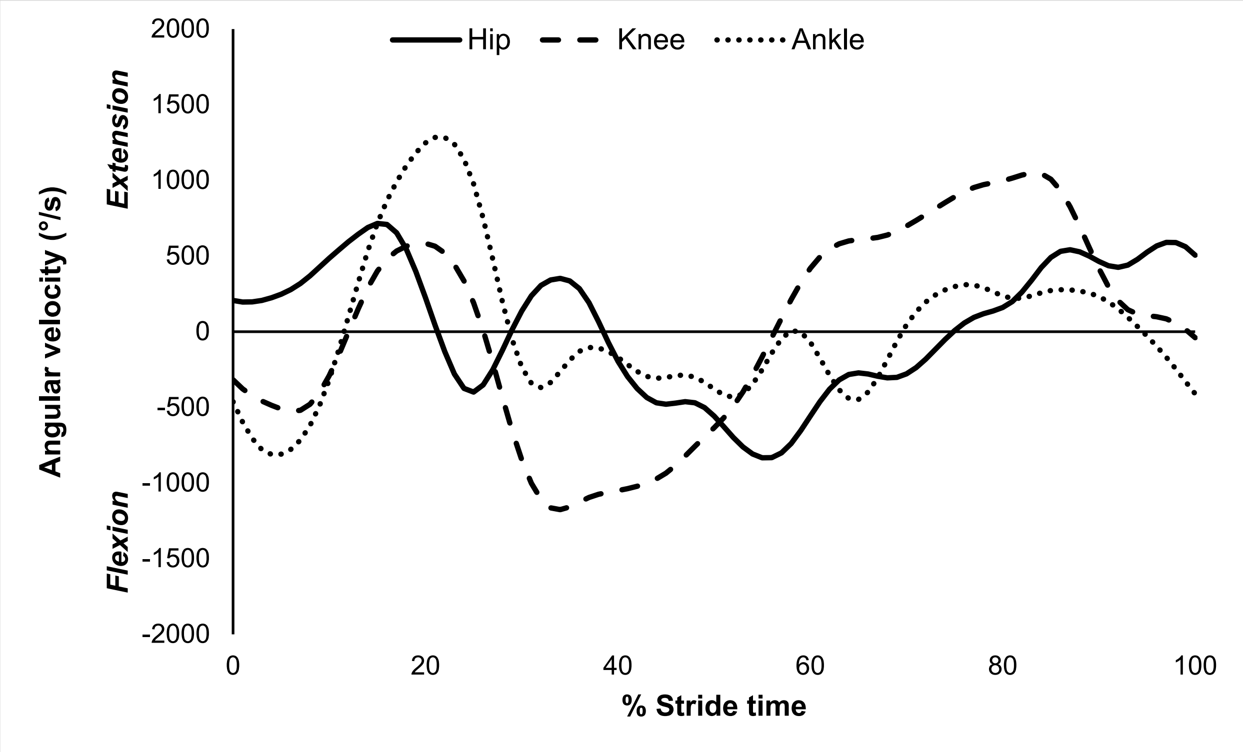

Figure 19.5. Hip, knee and ankle angular velocities over one stride for fifth placed Elaine Thompson.

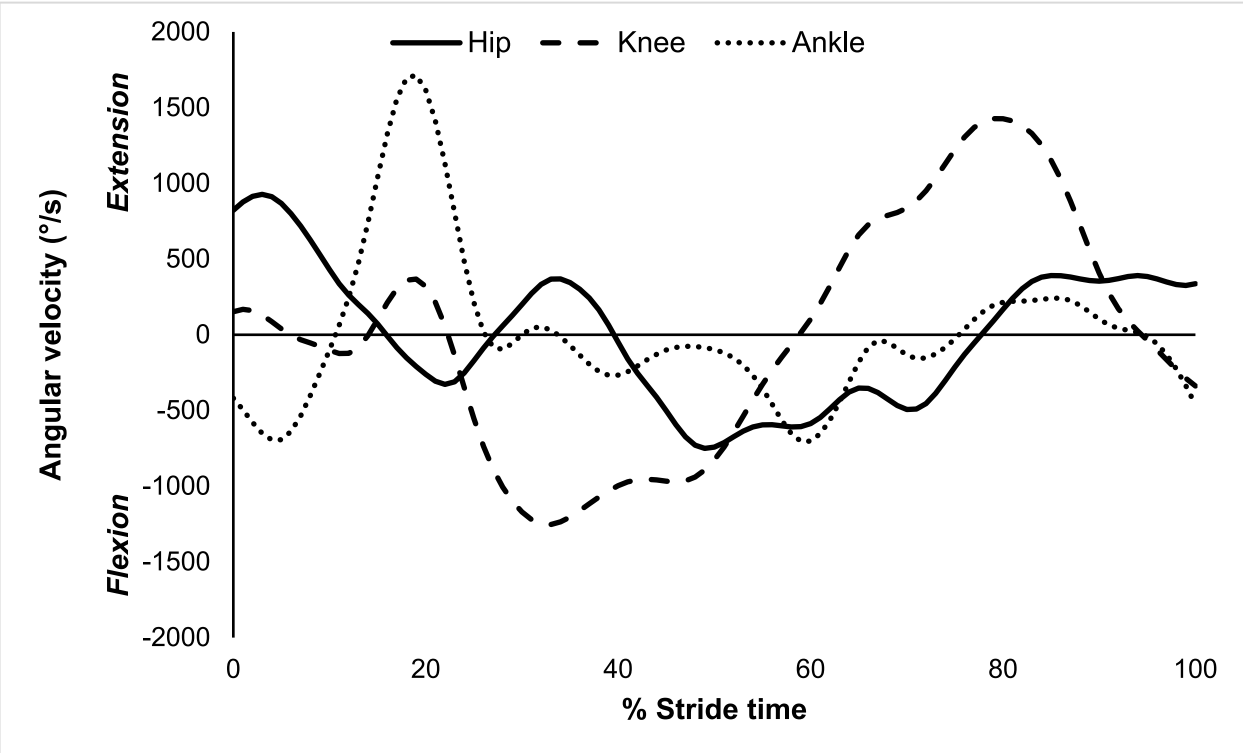

Figure 19.6. Hip, knee and ankle angular velocities over one stride for sixth placed Michelle-Lee Ahye.

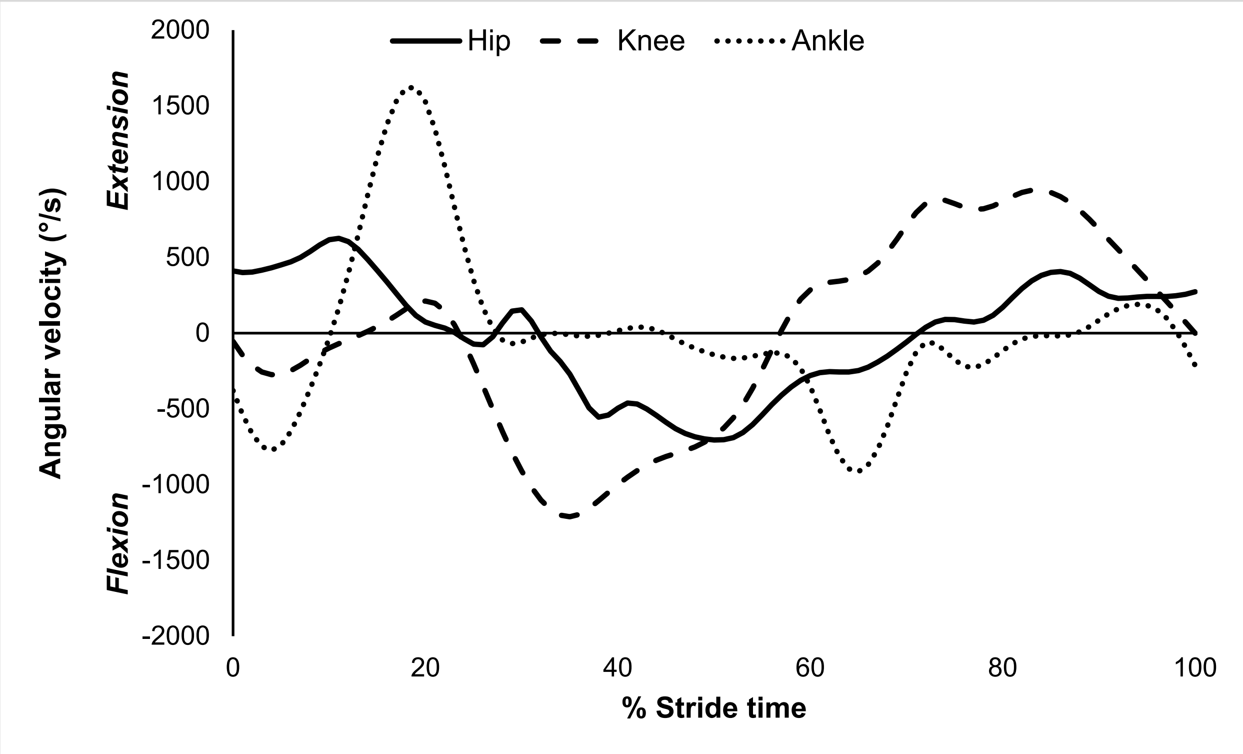

Figure 19.7. Hip, knee and ankle angular velocities over one stride for seventh placed Rosangela Santos.

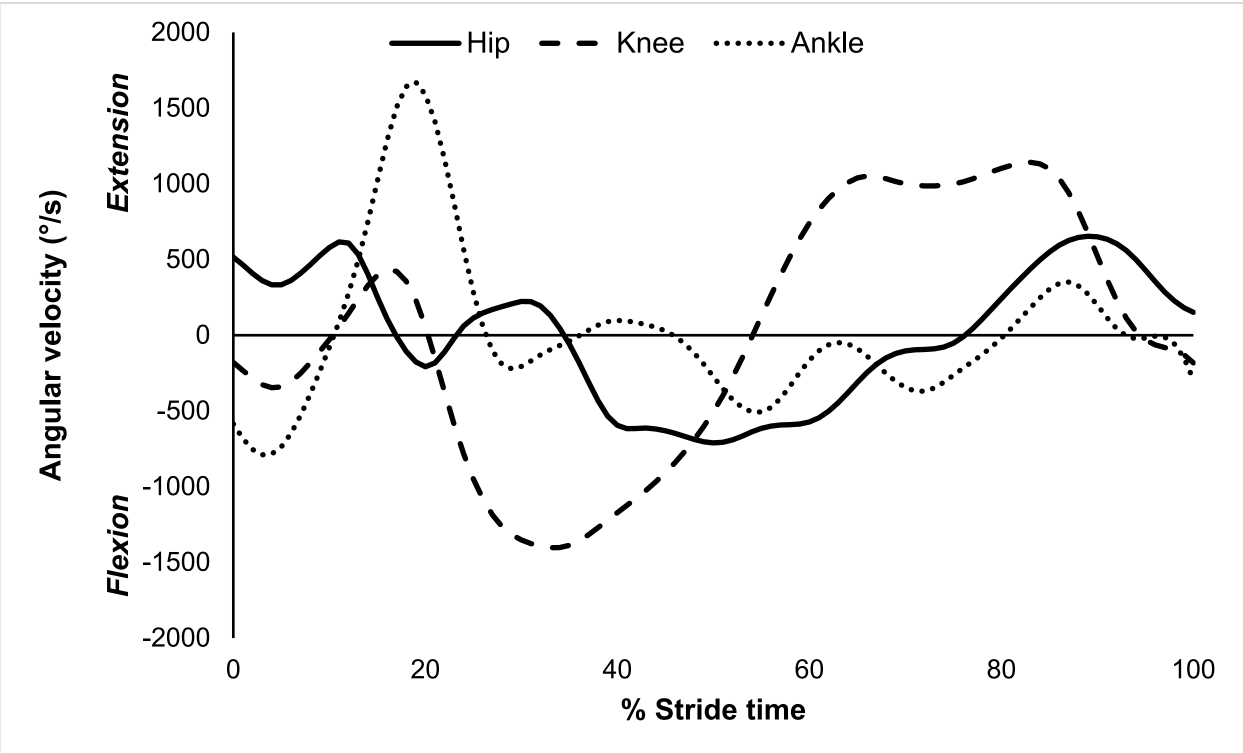

Figure 19.8. Hip, knee and ankle angular velocities over one stride for eighth placed Kelly-Ann Baptiste.

Final stage of the race

The following section displays key kinematic characteristics for the three medallists during the final two step (penultimate step and final completed step) before crossing the finish line.

Table 16. Step length, step rate and step velocity for the penultimate step for each of the medallists.

	Step length (m)	Step rate (Hz)	Step velocity (m/s)
BOWIE	2.45	3.97	9.72
TA LOU	2.24	4.46	10.00
SCHIPPERS	2.23	4.63	10.32

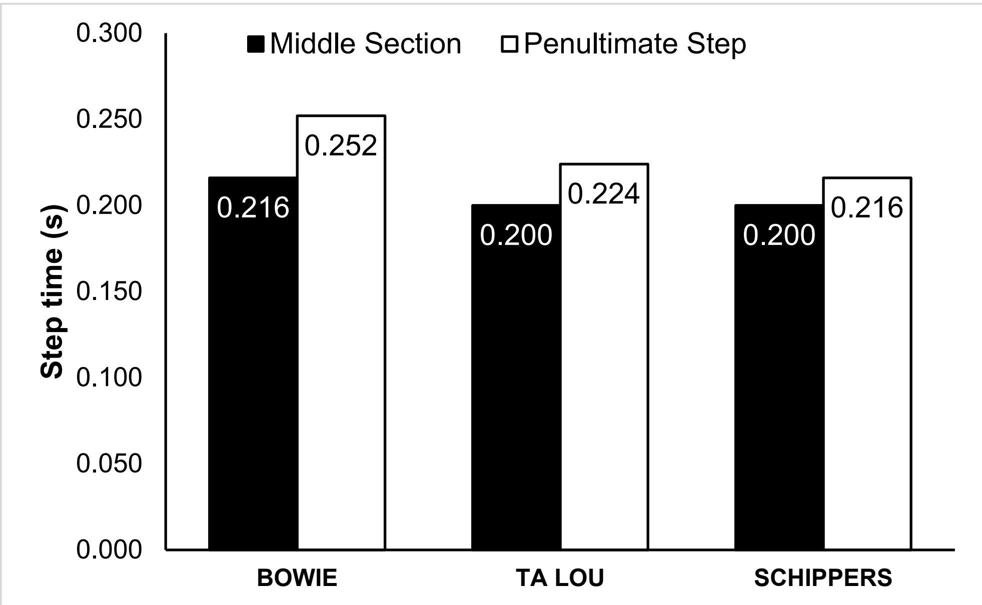

Figure 20. Comparison of step time of the penultimate step and the side-matched analysed step from the middle section of the race. Data shown for each of the medallists.

Table 17. Contact times and flight times for the penultimate step (PS) and final completed step (FS) for each of the medallists. Percentage increase or decrease in times from PS to FS are also displayed.

	PS contact time (s)	FS contact time (s)	Change (%)	PS flight time(s)	FS flight time (s)	Change (%)
BOWIE	0.100	0.092	−8.0	0.152	0.132	−13.2
TA LOU	0.092	0.096	+4.3	0.132	0.124	−6.1
SCHIPPERS	0.100	0.112	+12.0	0.116	0.140	+20.7

Table 18. Joint angles measured at touchdown of the penultimate step (PS) and final completed step (FS) for each of the medallists.

	BOWIE		TA LOU		SCHIPPERS	
	PS (°)	FS (°)	PS (°)	FS (°)	PS (°)	FS (°)
α	77.1	70.8	79.2	73.2	77.5	78.2
β	153.6	161.0	147.5	161.8	157.1	146.2
γ	145.3	144.4	140.1	137.8	138.6	134.5
ε	29.4	24.0	33.0	26.7	28.8	36.8
ζ	−4.8	10.7	−3.4	−12.7	20.5	7.3
η	−34.2	−13.3	−36.4	−39.4	−8.3	−29.5
θ	100.9	97.7	93.2	103.0	96.1	93.9
ι	115.4	125.4	110.8	117.5	121.8	107.1

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. Trunk angles (α) do not represent upper spinal curvature and trunk rotation which are quite prominent in the final steps of the race.*

Table 19. Joint angles measured at toe-off of the penultimate step (PS) and final completed step (FS) for each of the medallists.

	BOWIE		TA LOU		SCHIPPERS	
	PS (°)	FS (°)	PS (°)	FS (°)	PS (°)	FS (°)
α	79.8	74.8	80.6	78.5	83.8	79.1
β	170.0	176.0	166.0	161.9	165.6	169.2
γ	203.8	207.9	198.9	199.8	204.0	197.0
δ	115.8	104.5	120.1	115.5	98.3	105.9
ε	−32.5	−38.6	−30.7	−32.2	−30.0	−30.9
ζ	57.0	56.9	55.6	57.1	75.6	67.5
η	89.5	95.5	86.3	89.3	105.6	98.4
θ	48.7	46.3	45.9	42.0	45.6	50.0
ι	140.6	133.1	132.8	130.9	146.4	157.4

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. Trunk angles (α) do not represent upper spinal curvature and trunk rotation which are quite prominent in the final steps of the race.*

In an attempt to further describe the postural technique whilst crossing the finish line, Figure 21 presents the trunk angle, relative to the horizontal, during critical instants of the final two steps and at touchdown when crossing the finish line.

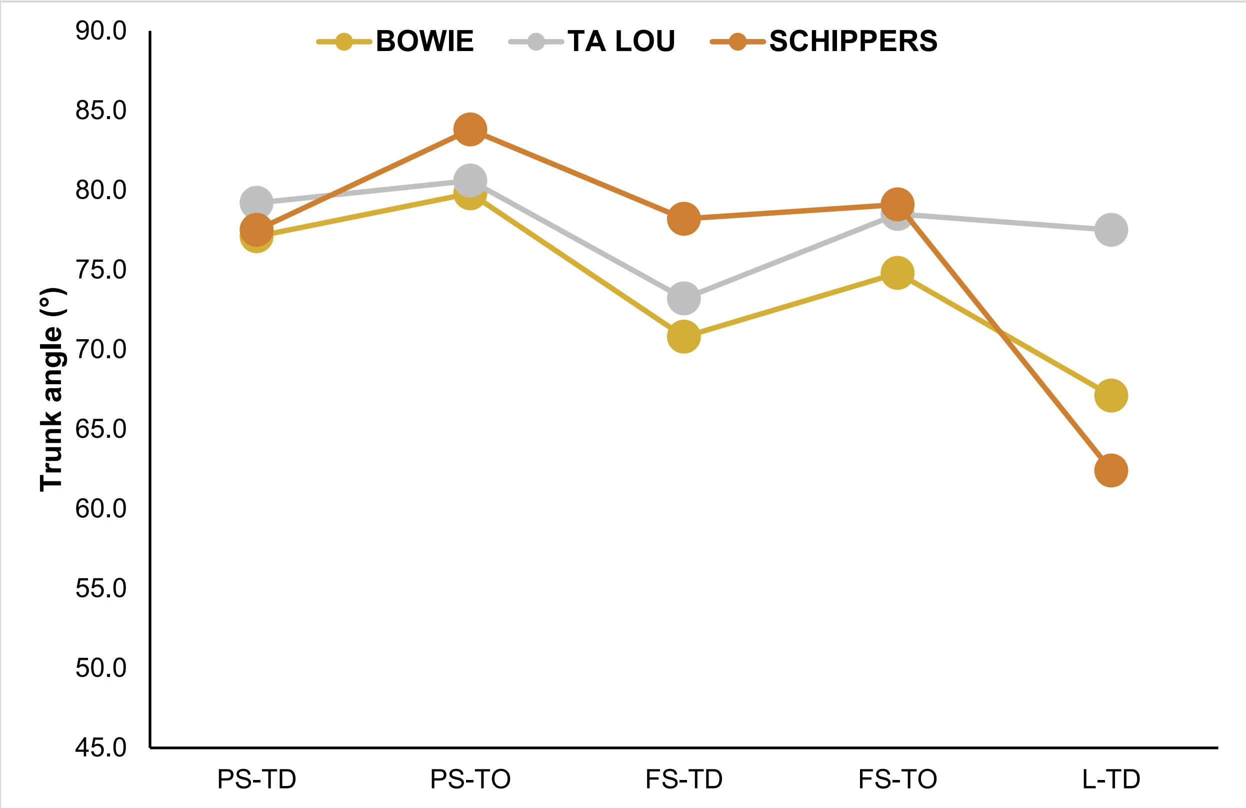

Figure 21. Trunk angle relative to the horizontal (angle α) at penultimate step touchdown (PS-TD) and toe-off (PS-TO), final completed step touchdown (FS-TD) and toe-off (FS-TO), and initial ground contact when crossing the line (L-TD). Data displayed for each of the medallists.

RESULTS – SEMI-FINAL 1

The following section of results presents temporal data based on split times from the first of the women's 100 m semi-finals. Athletes who qualified for the final are highlighted in blue.

Positional analysis

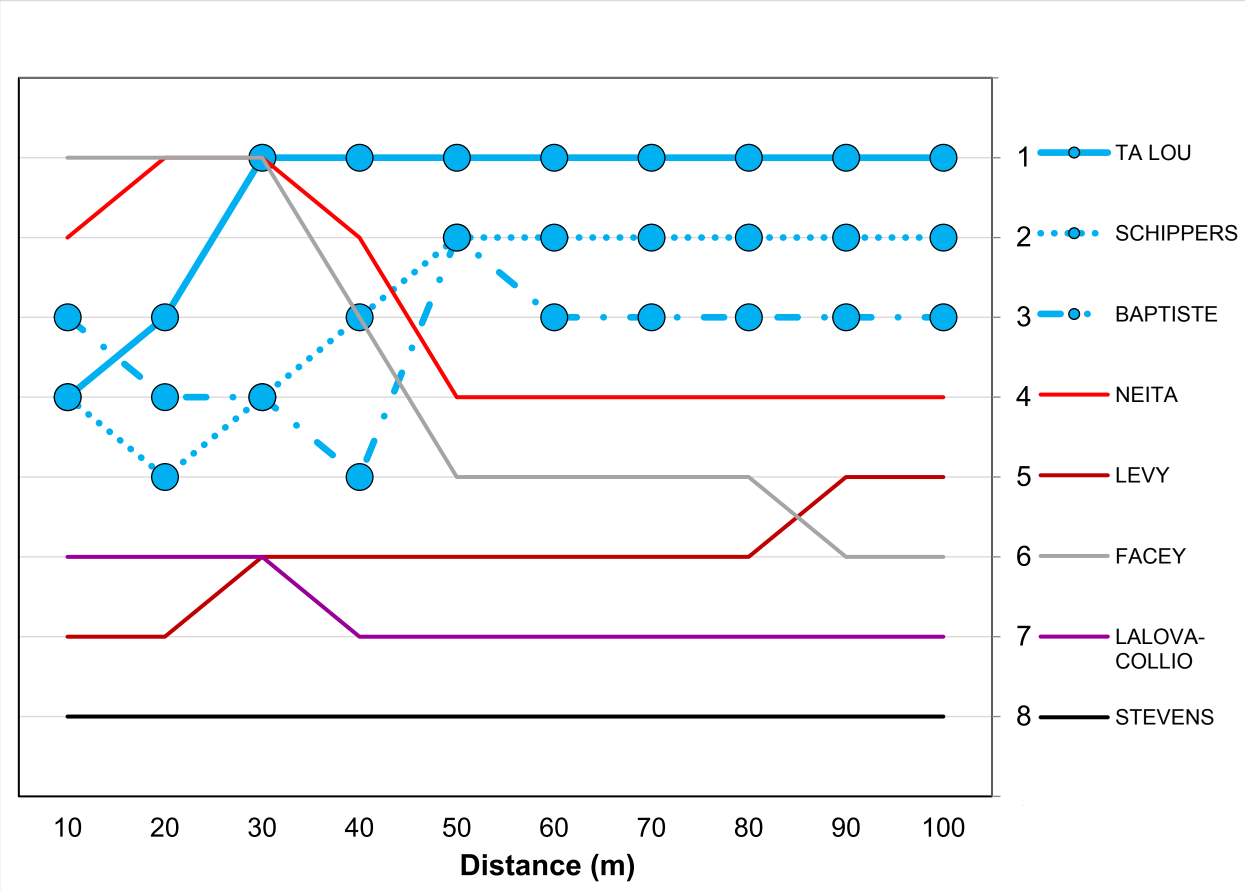

Figure 22. Race position of the athletes from semi-final 1 at each 10-metre split.

Note: *Positional analysis based on time to three decimal places.*

Speed analysis

Figure 23 (below) shows the mean speed over each 10-metre split for each of the athletes in semi-final 1. This was calculated based on the time taken to complete each split.

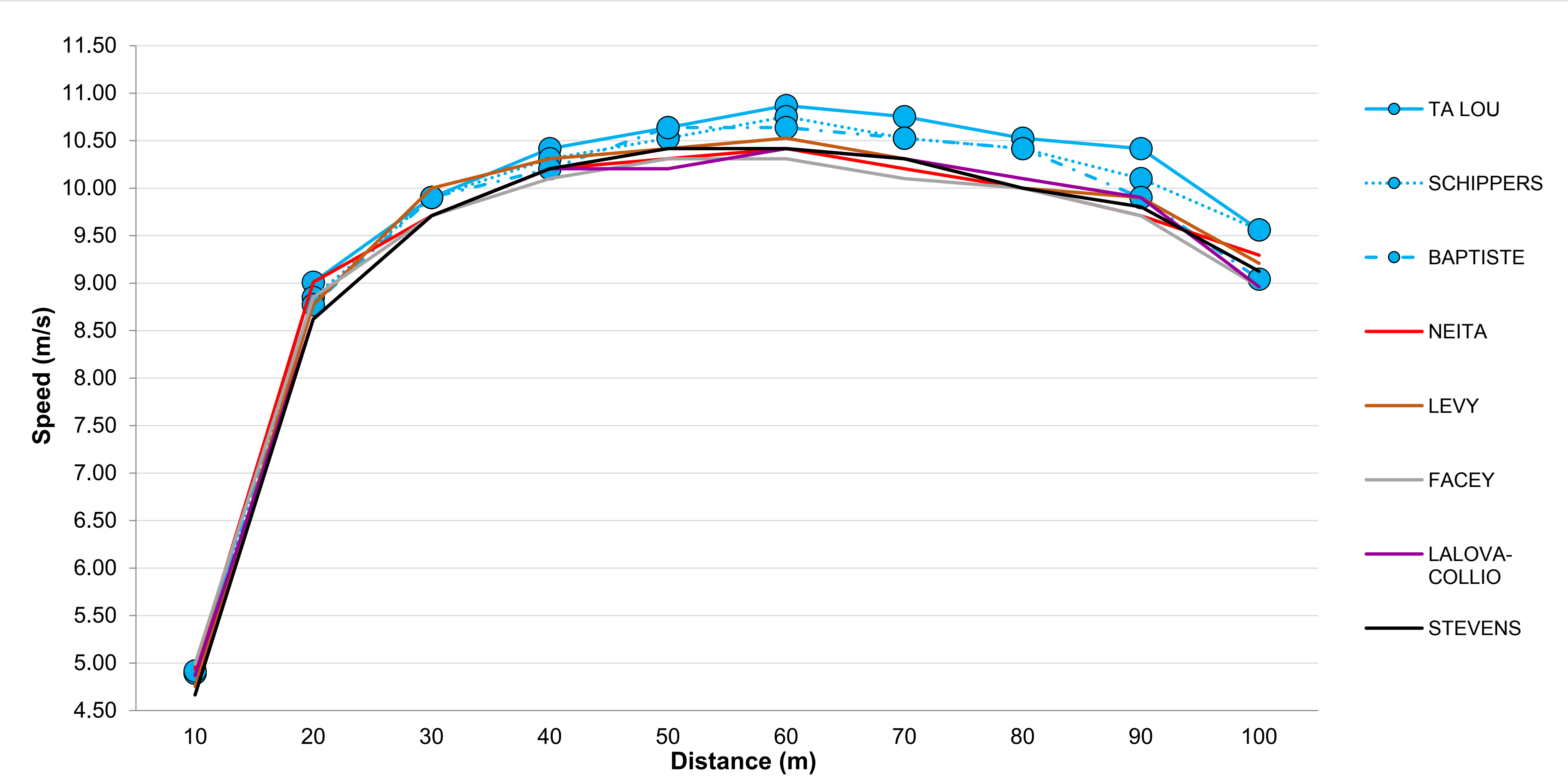

Figure 23. Mean speed over each 10-metre split.

Step length analysis

The following two figures display mean step length, based on step count data. Data are displayed as both absolute lengths and lengths relative to body height (1.00 = body height).

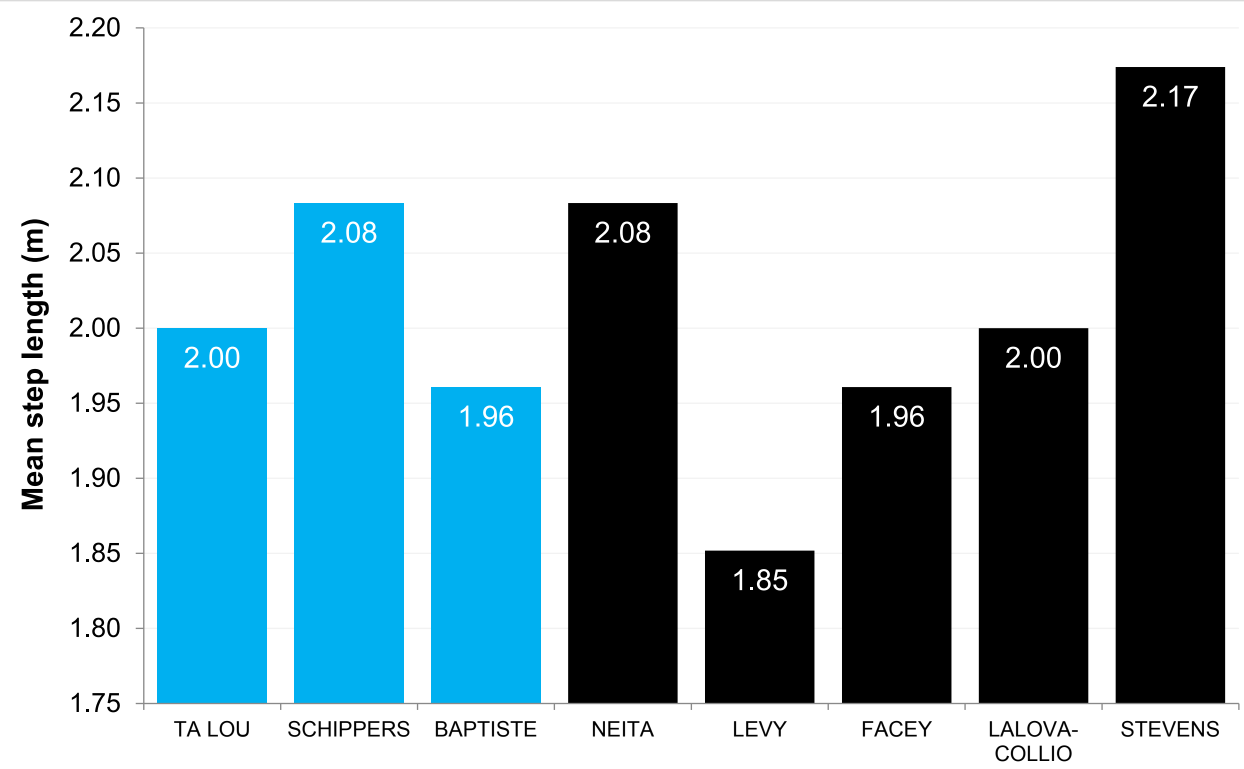

Figure 24. Mean absolute step length for each athlete over 100 metres.

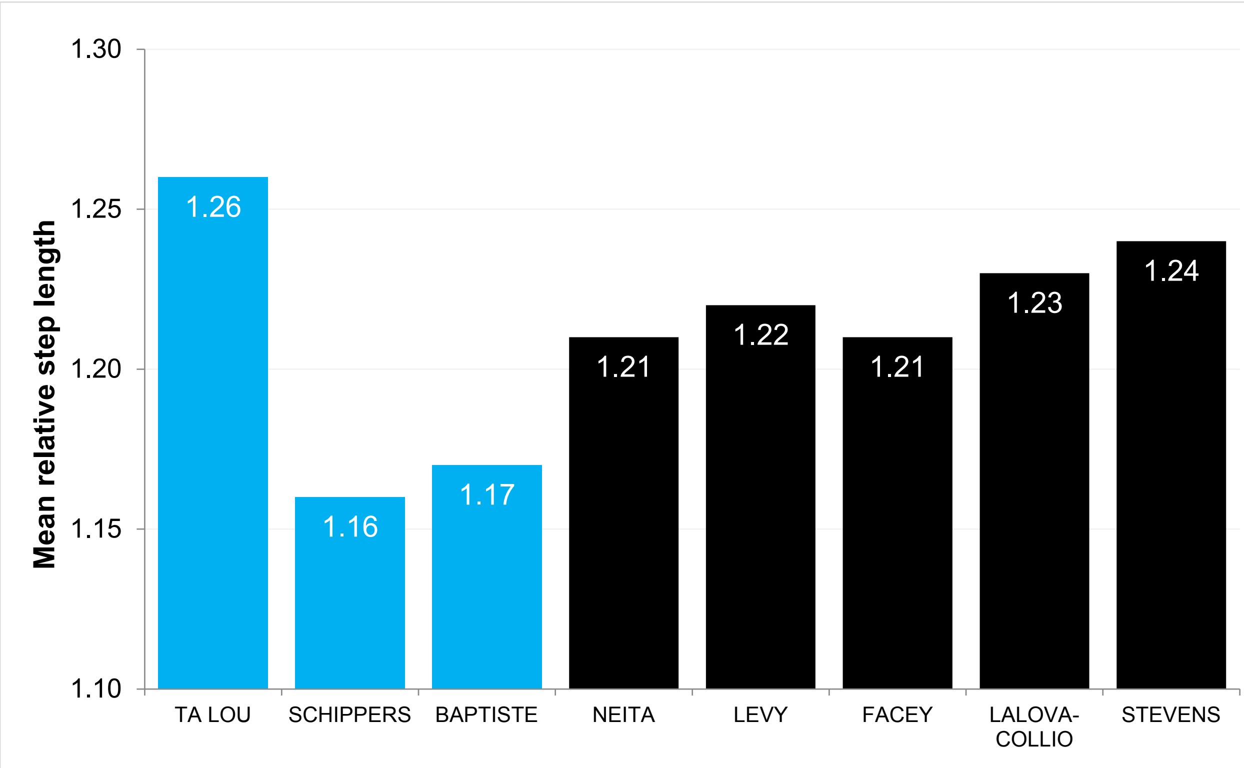

Figure 25. Mean relative step length for each athlete over 100 metres.

RESULTS – SEMI-FINAL 2

The following section of results presents temporal data based on split times from the second of the women's 100 m semi-finals. Athletes who qualified for the final are highlighted in blue.

Positional analysis

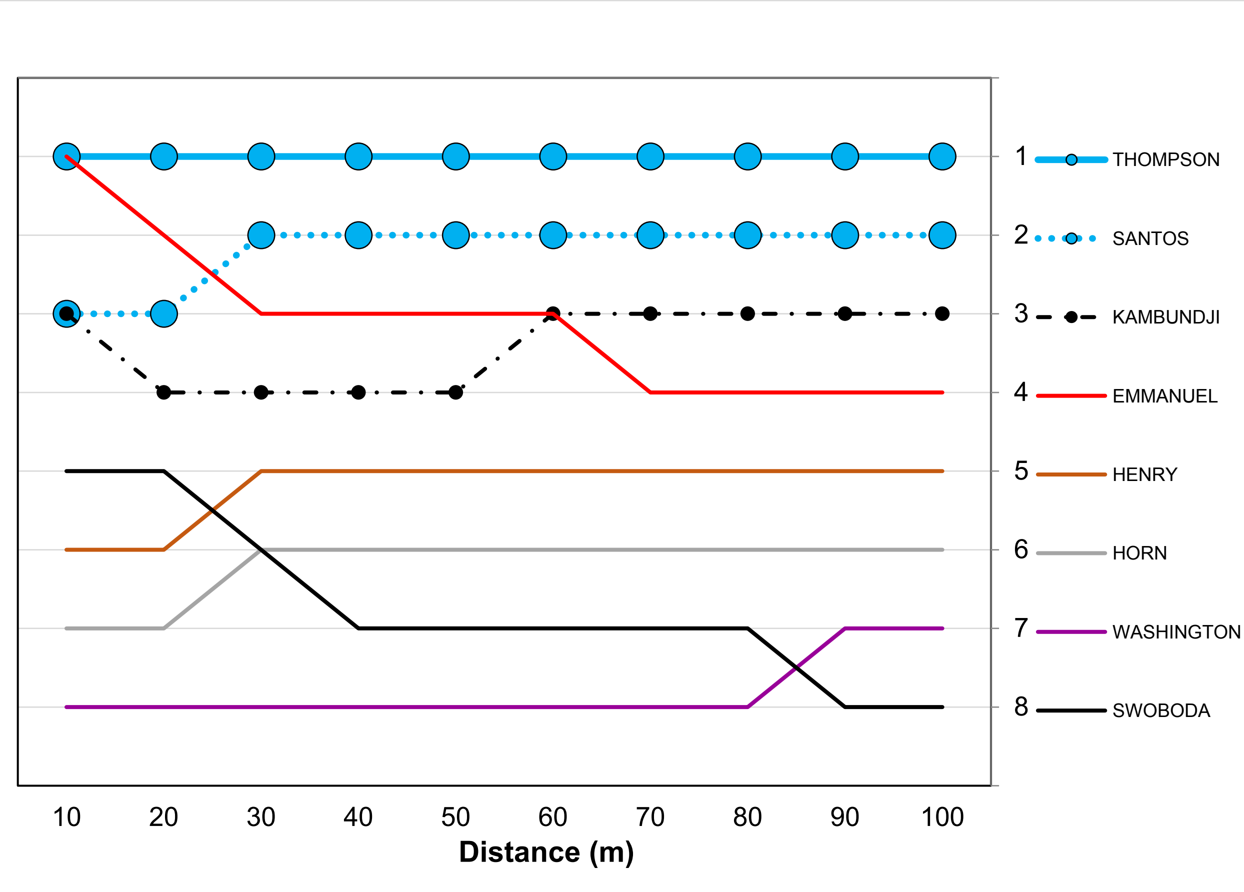

Figure 26. Race position of the athletes from semi-final 2 at each 10-metre split.

Note: *Positional analysis based on time to three decimal places.*

Speed analysis

Figure 27 (below) shows the mean speed over each 10-metre split for each of the athletes in semi-final 2. This was calculated based on the time taken to complete each split.

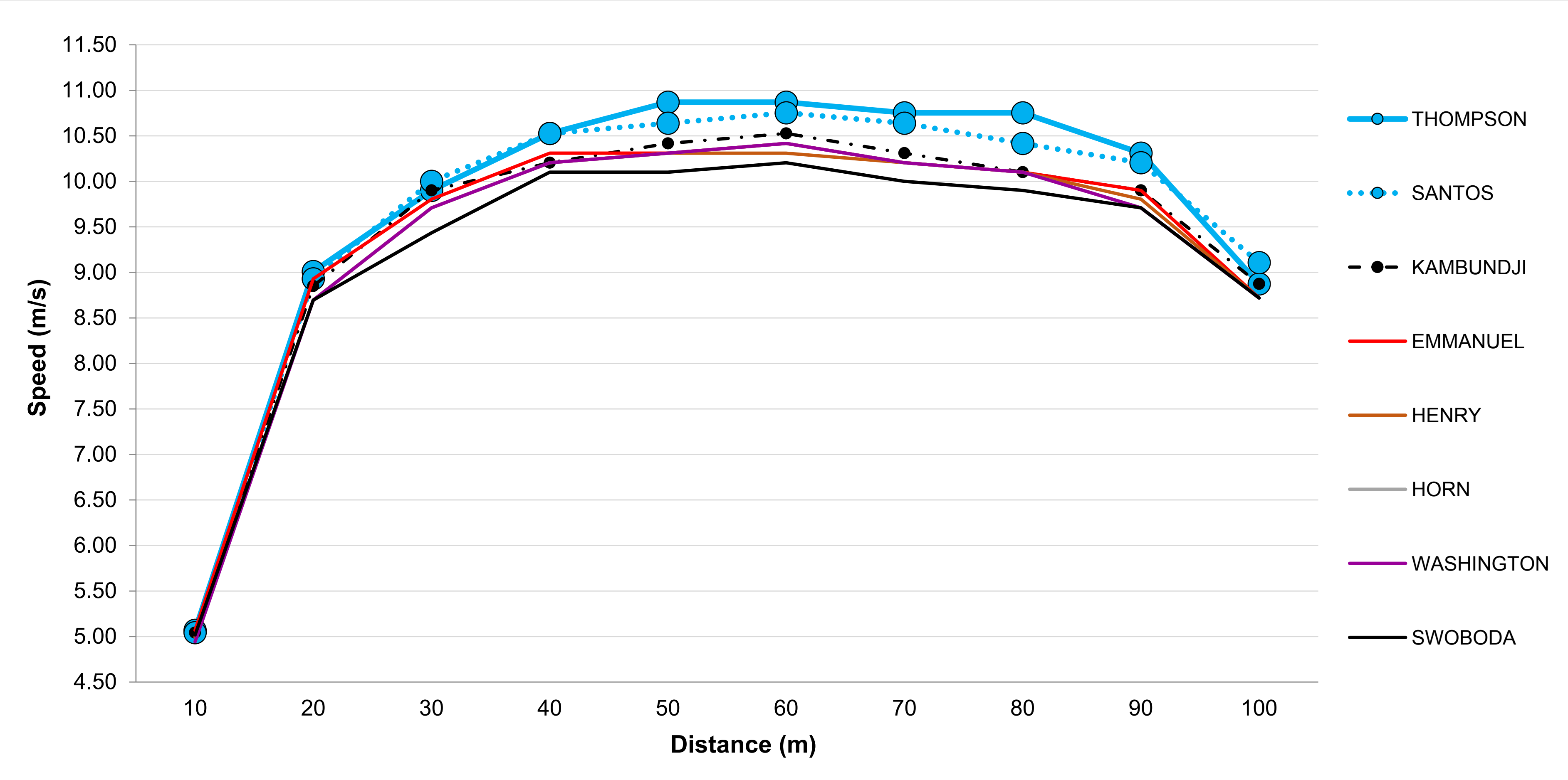

Figure 27. Mean speed over each 10-metre split.

Step length analysis

The following two figures display mean step length, based on step count data. Data are displayed as both absolute lengths and lengths relative to body height (1.00 = body height).

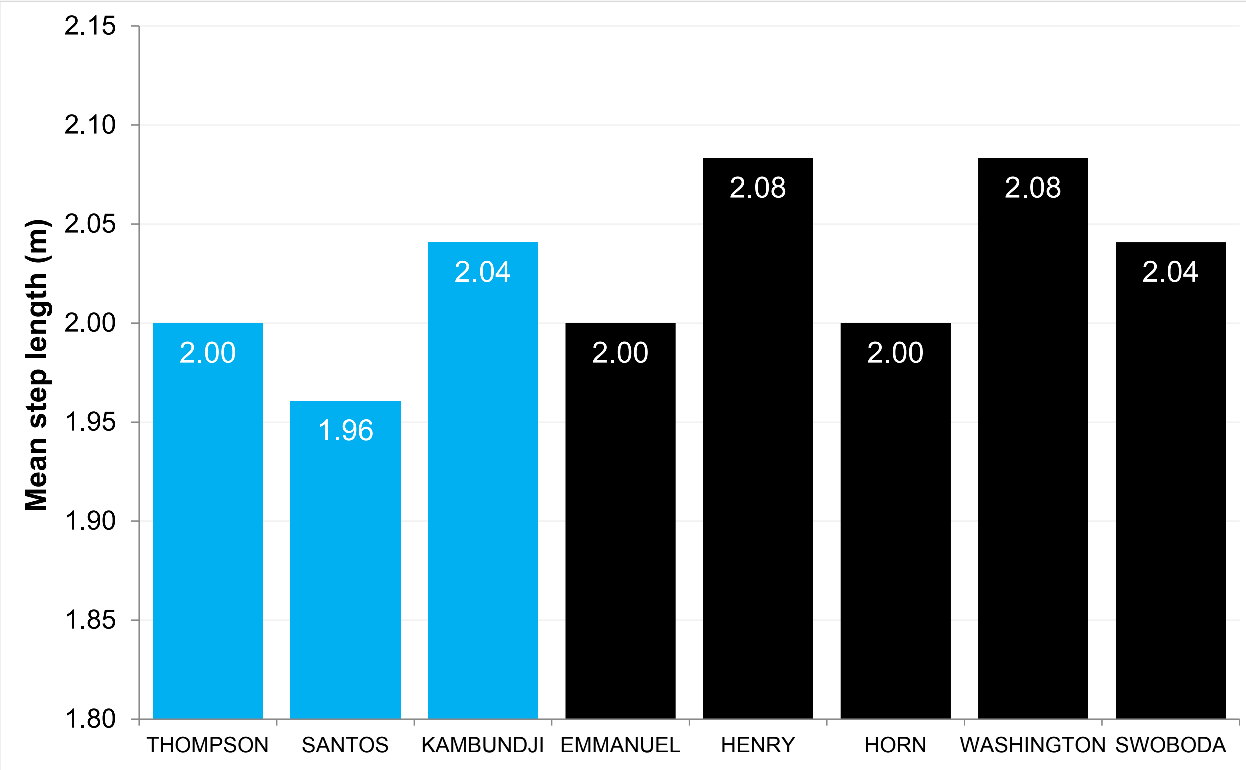

Figure 28. Mean absolute step length for each athlete over 100 metres.

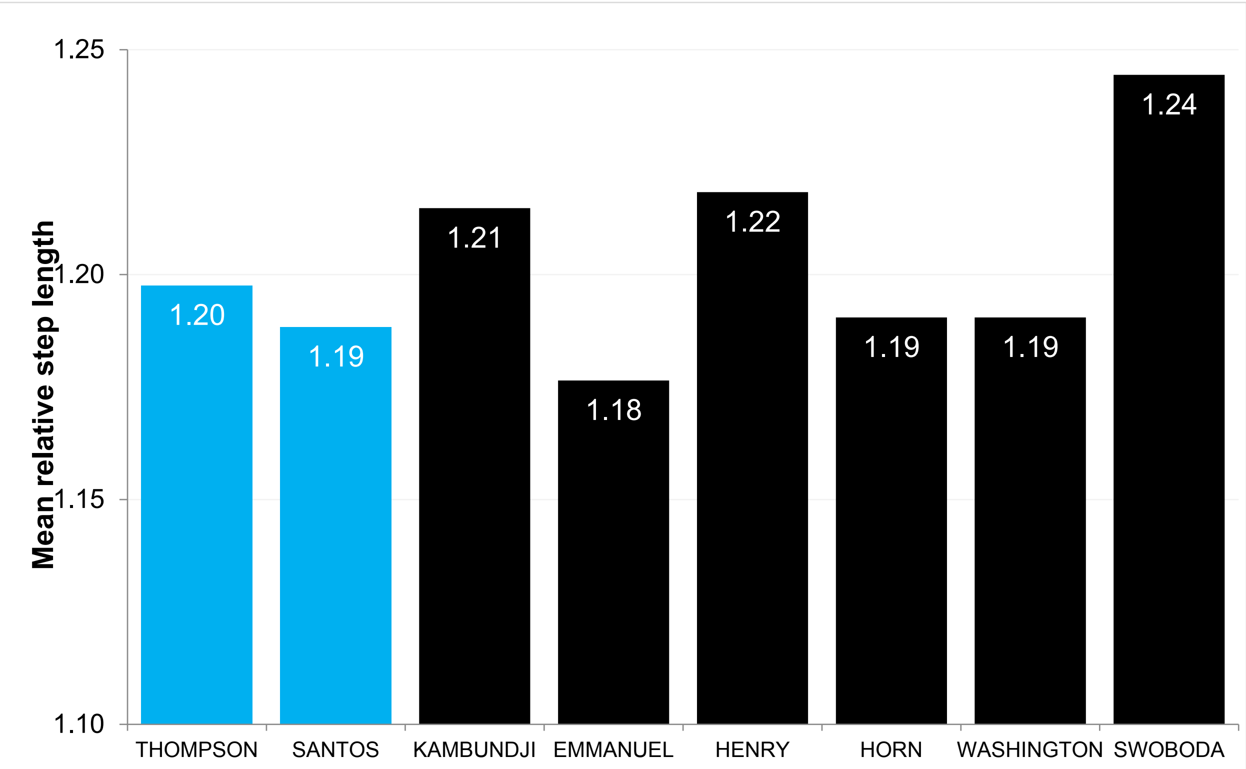

Figure 29. Mean relative step length for each athlete over 100 metres.

RESULTS – SEMI-FINAL 3

The following section of results presents temporal data based on split times from the third of the women's 100 m semi-finals. Athletes who qualified for the final are highlighted in blue.

Positional analysis

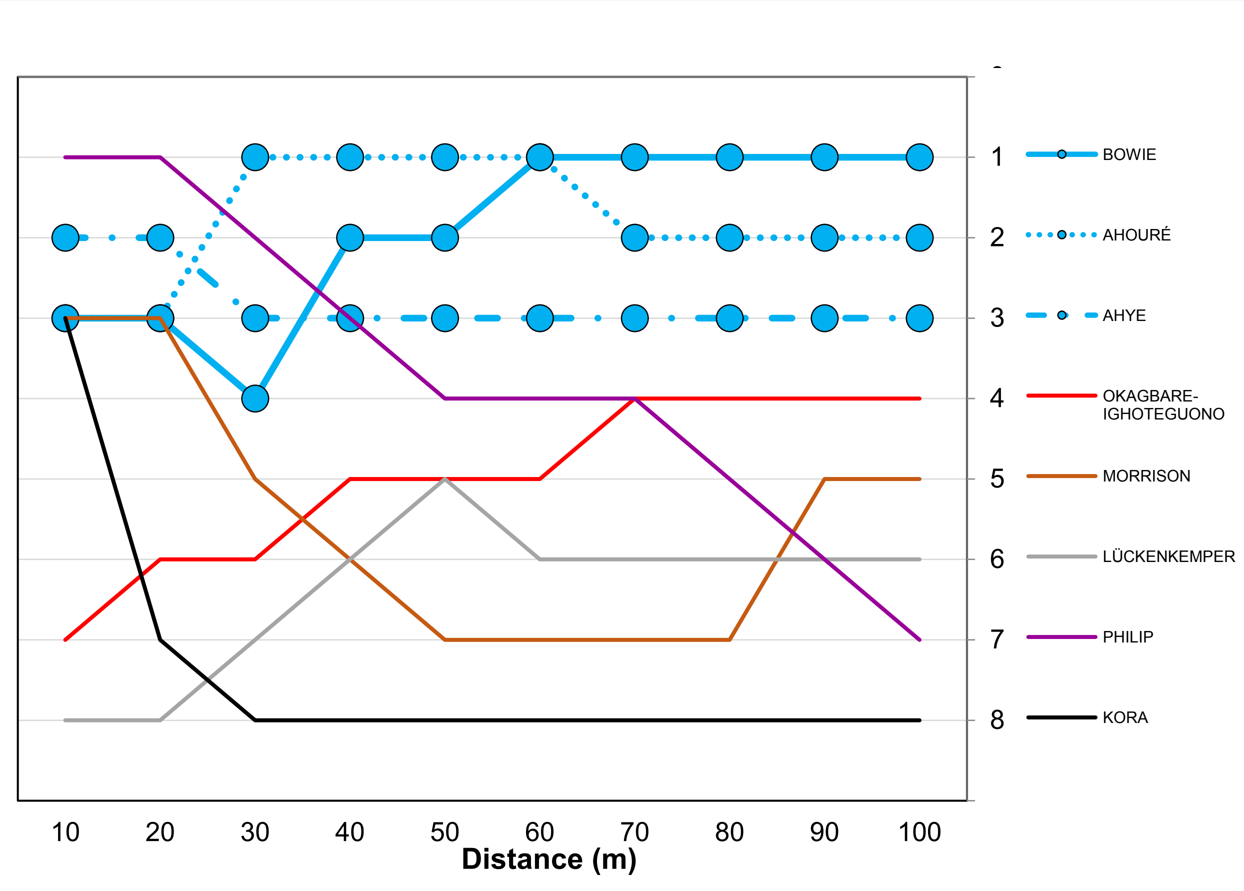

Figure 30. Race position of the athletes from semi-final 3 at each 10-metre split.

Note: *Positional analysis based on time to three decimal places.*

Speed analysis

Figure 31 (below) shows the mean speed over each 10-metre split for each of the athletes in semi-final 3. This was calculated based on the time taken to complete each split.

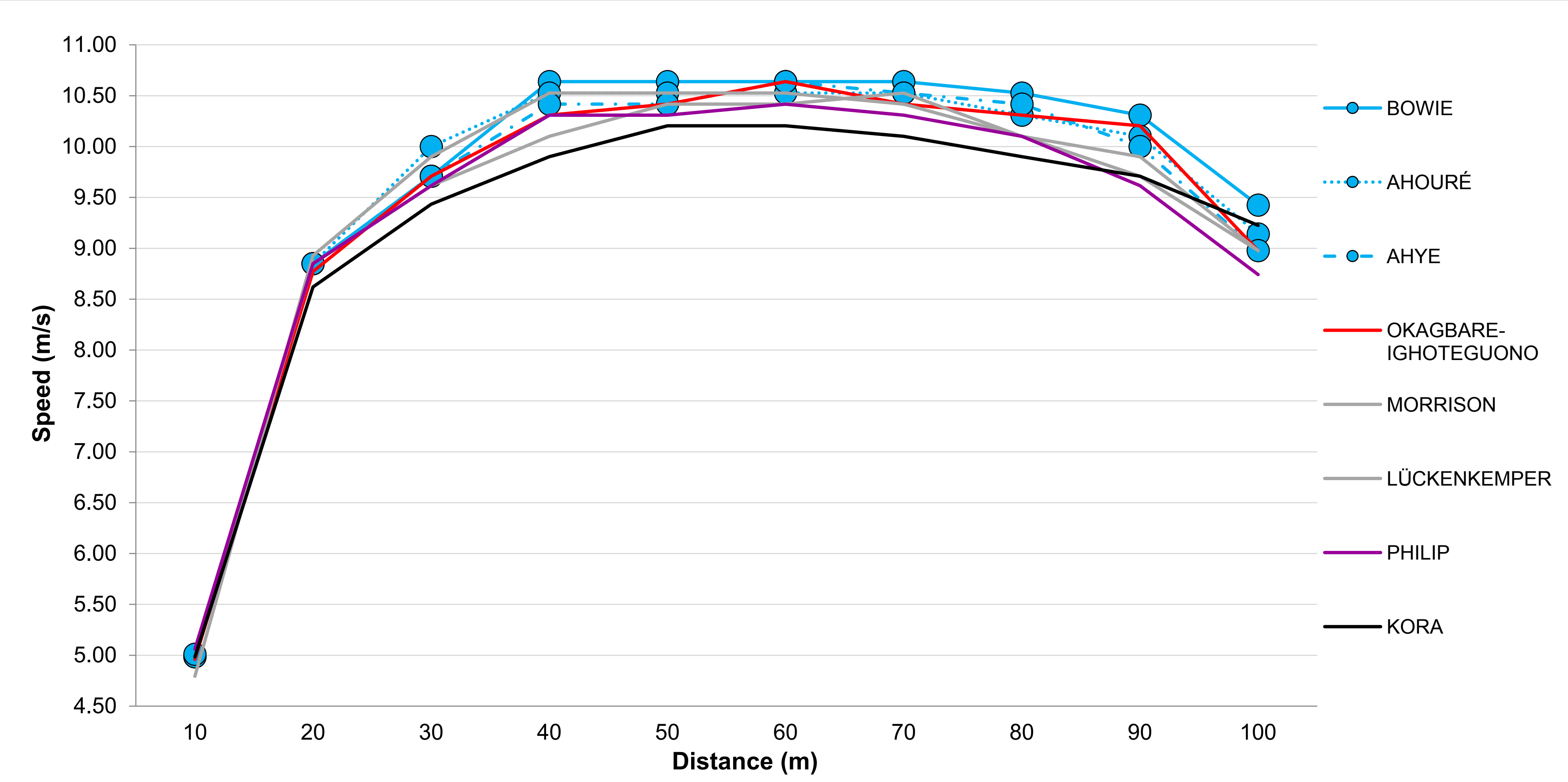

Figure 31. Mean speed over each 10-metre split.

Step length analysis

The following two figures display mean step length, based on step count data. Data are displayed as both absolute lengths and lengths relative to body height (1.00 = body height).

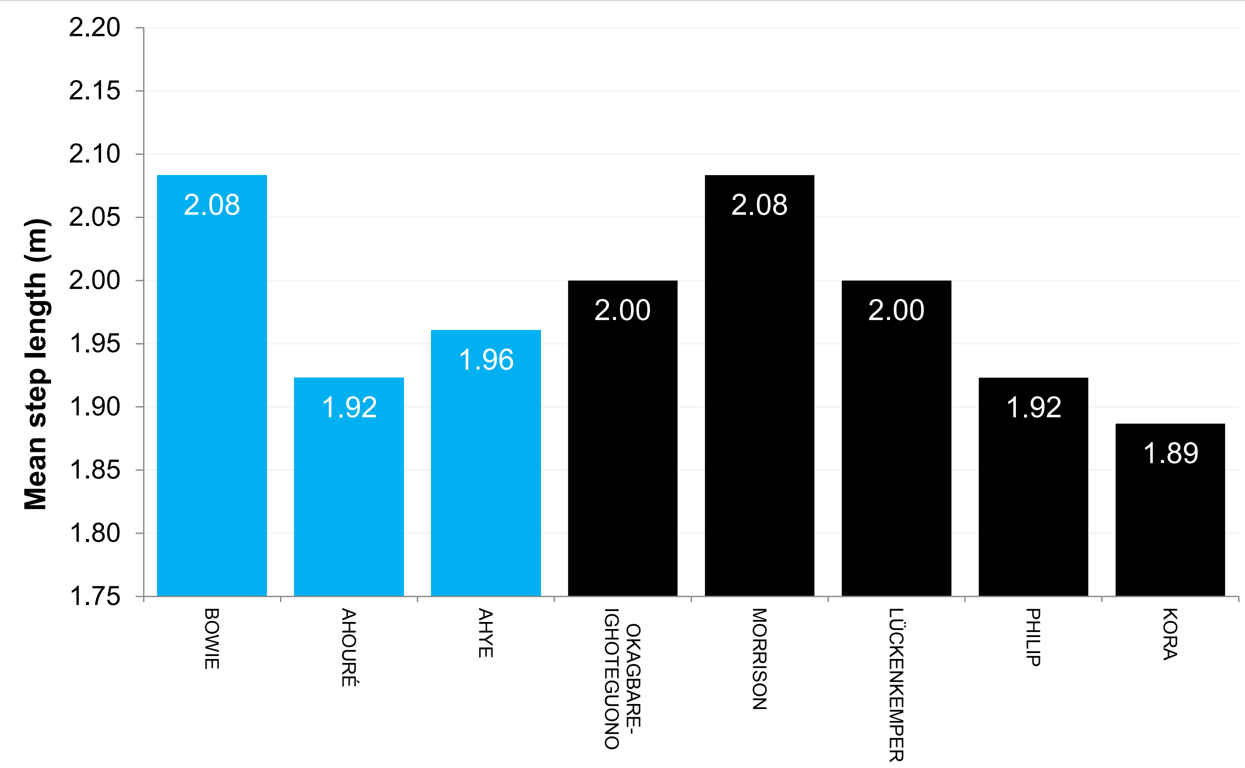

Figure 32. Mean absolute step length for each athlete over 100 metres.

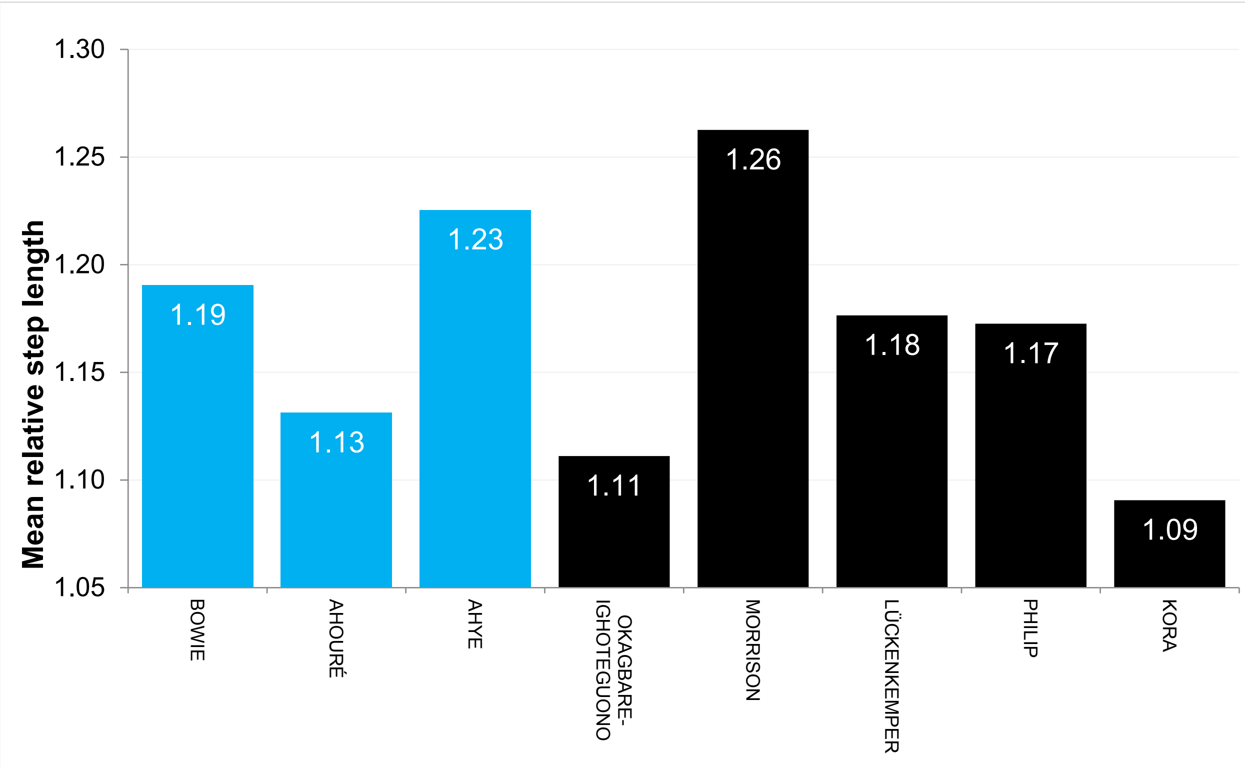

Figure 33. Mean relative step length for each athlete over 100 metres.

COACH'S COMMENTARY

Historical analysis and coaching commentary – Pierre-Jean Vazel

This commentary has a double ambition: to compare selected data from the extensive report made on women's 100 m during the 2017 World Championships (WC) in London with historical and little known research made on previous competitions, and give coaches guidance for using biomechanical data for training individualisation.

Acceleration phase

The present report confirms that maximum velocity is the parameter having the strongest association with the 100 m result, as the medallists reached the highest top speeds (Table 2.1, Figure 5), which is in accordance with the results from all the past major finals. The location of maximum velocity during 100 m races, or the length of the acceleration phase, are also of interest. This has been a subject of controversy over the years, regarding whether faster sprinters reach it later than slower ones, and if there is a gender difference to that matter. In London's women's final, the fastest 10 m splits were recorded between 30 m and 70 m, while the men's were found between 40 m and 80 m. Therefore, the idea that women reach it *later* than men needs to be reconsidered.

The first ever study on the acceleration phase in elite sprinters was done with 1928 Olympic champions Percy Williams (men's 100 m) and Myrtle Cook (women's 4x100 m) on an indoor track in Toronto (Best & Partridge, 1929). Williams accelerated until the 45-50 yard section (approximately between 40 and 45 metres) reaching top speed after 5.4 seconds into the race. It took a shorter distance for Cook to accelerate to top speed, between 35 and 40 yards (30 and 40 metres), but almost in the same time frame as her male counterpart, 5.2 s. During the 1950s, the first systematic analysis in competition, using either cinematography (camera) or speedogram (pulling a thread) were performed in the USSR. The conclusions of the authors (Chomenkov, 1953; Ozolin, 1953) go against what is the current belief: comparing velocity curves of sprinters of various levels, as well as different races for the same elite sprinters, they observed that the fastest races are the ones where maximum velocity is reached after a shorter distance, while slower runners, including women, need a longer path, and stated that it is advisable to hit top speed as soon as 18 m into the race! This concept was still popular in to the late 1960s, as the analysis of the world record (11.1 s hand time, 11.34 s auto time in Leningrad in 1965) by Wyomia Tyus showed that she reached her top speed 5.7 seconds into the race, earlier than slower women, and later than the fastest male sprinters (Ionov, 1967). This is contradictory to statistical trends derived from data collected from hundreds of races by East Germans from 1972 (Hess, 1978), showing that both groups of fastest male and female sprinters (100 m result of 10.16 s to 10.50 s for men and 11.10 s to 11.40 s for women) were reaching 100% of their running velocity in the 60-80 m section rather than in the 30-60 m section for the slower groups.

Split times for the 100 m of the 1983 and 1987 WC finals showed that women's acceleration path was shorter than men's (Mero, 1987; Moravec, 1990), while the 1988 and 1992 Olympic finals showed conflicting results, probably because female races were affected by winds (Brüggemann, 1990; Arnold, 1992). The use of laser gun during the 1996 Olympic Games (OG) (Türck-Noack, 1998) with a larger number of subjects provided more precise data for the comparison of location in space and time of maximum velocity in men and women:

1996 OG	**No. of subjects**	**Mean 100 m time [range] (s)**	**Distance to max. velocity (m)**	**Time to max. velocity (s)**
Men	31	10.23 (9.84-10.49)	53.6	6.05
Women	21	11.22 (10.94-11.51)	49.6	6.17

Men have indeed a longer acceleration than women, if distance is the reference, but women reach maximum velocity at about the same time or slightly later than men, if time is the reference. This trend was confirmed with the same methodology during 1997 and 2007 WC (adapted from Kersting, 1997; Matsuo, 2010b):

1997 WC	**No. of subjects**	**Mean 100 m time [range] (s)**	**Distance to max. velocity (m)**	**Time to max. velocity (s)**
Men	31	10.19 (9.86-10.47)	55.7	6.21
Women	24	11.26 (10.83-11.62)	52.1	6.41
2007 WC	**No. of performances**	**100 m range (s)**	**Distance to max. velocity (m)**	**Time to max. velocity (s)**
Men	63	9.85-10.86	58	6.4
Women	69	10.99-11.98	52	6.4

This was again confirmed by the most extensive study to date (Matsuo, 2016), using all the 10 m splits and laser data collected in the literature or recorded by the authors from 1988 to 2016):

	No. of performances	Mean 100 m time [range] (s)	Distance to max. velocity (m)	Time to max. velocity (s)
Men	919	10.45 (9.58-11.18)	54	6.12
Women	843	11.80 (10.54-13.08)	48	6.28

These data have implications for coaching. The duration of the acceleration is associated with higher maximum running velocity and final performance at 100 m. To achieve this, athletes must manage to apply the greatest amount of force into the ground in an overall horizontal orientation for the longest time, while ground contact duration gets shorter at each step and the overall orientation gets more and more vertically-oriented, until maximum velocity is reached and forward acceleration is null. However, since maximal acceleration, maximal running velocity and 50 m sprint times have been associated with maximal value of effective power relative to body weight in male and female sprinters (Ikuta, 1971), promising research is being done to develop individualized training to optimize the improvement of horizontal power by the used of resistance training (Cross, 2017).

High velocity running phase

The measurements presented in the report from page 16 were taken in the 47-55.5 m section, where most of the women were running at or very close to their maximum velocity, whereas men were about to end their acceleration phase. The longest steps were made by the three medallists Tori Bowie, Marie-Josée Ta Lou and Dafne Schippers, 2.26 m, 2.20 m and 2.30 m, respectively. The data for all the finalists fell within the large range existing in the all-time sub-11 s women performers when they set their lifetime best at 100 m: between 2.52 m for Marie-José Pérec (10.96 s in 1991) and 2.02 m by Marlies Göhr (10.81 s in 1983). Step frequency didn't seem to be a decisive factor for medals in the London 2017 final, and the highest and lowest rates, 5.00 Hz for Kelly-Ann Baptise and 4.59 Hz for Schippers were very similar to what was found in the men's final: 5.00 Hz for Akani Simbine and Su Bingitan, and 4.63 Hz for Reece Prescod. It was also within the large range found in the all-time best sprinters: 4.16 Hz for Pérec and 5.10 Hz for Göhr (the highest ever was recorded in a slower 100 m for Göhr, 5.51 Hz between 54 and 62 m during a 10.97 s race in Tokyo 1984, cf. Miyashita, 1992). The fact that step frequency is about the same in women and men (the highest recorded for men's history during a lifetime best under

10 s is 5.15 Hz for Quentin Butler for 9.96 s in 2015) implies that the higher velocity in elite male sprint is due to longer steps. However, these longer steps might be attributed to higher stature more than supposedly great gender differences in power or technique (direction of force application). Indeed, the men's London finalists (from 1.72 m for Su to 1.96 m for Usain Bolt) are taller than women (from 1.59 m for Ta Lou to 1.78 m for Schippers) but when step length relative to body height (relative SL) is observed, the advantage is reduced to minimal for men. Marie-Josée Ta Lou had the same step length relative to her body height as Usain Bolt (1.38). This backs up historic records being close between women and men, 1.41 for Christine Arron (during her 10.73 s in 1998) and 1.44 for Leroy Burrell (during his 9.85 s in 1994).

Another way to look at the difference of power between elite men and women is to measure how much time they need to spend on the ground to apply enough force to run at (or close) maximum velocity. From Figure 10, contact times among women's London finalists ranged between 0.088 s (Ta Lou, Baptise) to 0.104 s (on right leg for Schippers and Elaine Thompson). This is close to the 0.084 – 0.104 s range found in the men's final. The shortest contact times ever recorded at maximum velocity for elite women are 0.071-0.076 s for world record holder Florence Griffith-Joyner in Seoul 1988 Olympic final (10.54 s wind assisted; Hlína, 1990) and 0.078 s for Göhr in a 10.94 s race (Müller, 1988), which are very close to what was found in elite men (0.077 s for Tyson Gay in 2009, 0.078 s for Harvey Glance in 1986). To sum-up, sub-10 s male sprinters generally tend to have slightly shorter contact times than sub-11 s females, but it implies that they must produce much more power in doing so because they need to move forward a heavier body (mean value: 78 kg vs. 59 kg).

London's biomechanical report provides the deepest analysis ever published on kinematic parameters for elite female sprinters in competition conditions. The comparison between both legs will give hints to coach regarding imbalances, but it is beyond the intent of the report to determine whether they are coming from anthropometric conditions or muscular deficiencies. However, such discrepancies have been spotted in the last 2 world record holders, Evelyn Ashford (Mansvetov, 1987) and Florence Griffith-Joyner (Hlína, 1988). Given the fact that the running velocity for London's finalists were in the same range (cf. Table 4, with the notable exception of 2017 World leader and favourite Thompson, who was not in shape during this race), no trend emerges from the angular parameters recorded at touchdown and toe-off. The criteria to assess the efficiency of the sprinting motion have been described and quantified in previous biomechanical reports at WC competitions (Susanka, 1983 ; Ito, 1994 ; Kersting, 1999 ; Fukuda, 2010) and studies of 100 m world record holders (Mansvetov, 1987; Tabachnik, 1987; Levchenko, 1989). From this literature, here are selected parameters that were found (or not) to be associated with running velocity at the top speed phase.

At touchdown (Figure 17, Tables 10 & 11):

- Ankle extension (larger angle ι) is correlated with top speed. Dafne Schippers (3rd in London's final) and Murielle Ahouré (4th) had on average the largest angles, unlike Tori Bowie (world champion).
- Hip and knee extension has no relation with top speed, hence we are not looking for high or acute angle but optimum value. Bowie had the lowest knee angle of all finalists.
- Between-thigh angles (angle η) should visually be parallel (knees at the same position relative to the hips) which indicates a fast swing leg coming up in front. Kelly-Ann Baptiste (8th) was in line with this model unlike Bowie and Marie-Josée Ta Lou (2nd), whereas Schippers had a pronounced imbalance with an inefficient swing of the left leg during right foot contact.

At toe-off (Figure 18, Tables 12 & 13):

- Hip flexion (knee lift, angle δ) is not correlated with top speed. Dafne Schippers and Kelly-Ann Baptiste had the highest knee lift, whilst Tori Bowie was amongst the lowest. This position is not associated with higher running velocity, which means that an optimum angle is the most effective (knee pointing forward, not pointing upward), even if at individual level, the best sprinters feel that the knee is coming up higher and easier as they reach top form.
- Hip extension (angle γ) – smaller angle correlated with top speed indicating that the leg won't stay too long on the ground and will swing earlier, as shown in Elaine Thompson (5th), Rosangela Santos (7th) and Baptiste. By contrast, world champion Bowie had the largest hip extension.
- Knee extension (angle β) – smaller angle correlated with top speed for the same reason explained for the hip extenstion, demonstrated by Ta Lou and Santos. Faster sprinters also have a smaller knee extension at toe-off than at touchdown, as seen in Santos. Bowie was again out of the model, with the largest knee extensions at toe-off, more extended than at touchdown.

These data also carry implications for coaching. Tori Bowie was an exception to the model for most of the parameters, yet she is the world champion. This fact alone is enough to question general trends applied to elite athletes, especially the ones that mix male and female athletes. While some world record holders have been very close to that model (Florence Griffith-Joyner or Marlies Göhr), some others were not (Evelyn Ashford). More research also needs to be done to associate angular kinematic parameters with anthropometric features and muscular strength levels to really assess the technical efficiency of an athlete, and to confront it with the cues used by coaches and athletes. In that respect, Kelly-Ann Baptiste, whose running form mostly matches the models, accepted to explain what her technical intentions are in the max speed phase: *"Technically I want my hips to be up and my foot strike to be 'under me', not over-striding or over-reaching. Some cues I use are to literally tell myself 'hips up' or 'get my foot down' but I mostly vizualize what I would like to execute".*

Statistically, the high velocity phase has a higher correlation with 100 m time than the acceleration and deceleration phases. However, even with all-out effort, elite sprinters usually don't reach the same velocities during training as they do during competition. Research in East Germany showed that during training tests, female sprinters were running about 2% slower in the acceleration phase (0-30 m) than their best time in competition, and that the biggest difference was in the top speed phase (30-60 m section), being 6% slower than in competition. A large range was also found between individuals, from 5 to 8% (Hess, 1990) and interestingly, the larger the difference in time, the larger the difference in the post-race lactate level. This suggests that the sprinters who run relatively fast in competition are able to better mobilize their glycolytic energetic potential with adrenaline under competition conditions. Anecdotal data indicate that this psychomotor regulation results in longer steps in competitions compared to training tests, while under the same conditions, whether training or competitions, improvements usually mainly come from a higher step frequency (again, with individual variations). The difference between training and competition, timed electronically in East Germany, led the researchers to implement from 1963 a pulling device in order to duplicate the competition running velocity in training conditions (Gundlach 1964), using a light traction force of 2.0-2.5 kg, while focusing on muscular relaxation. Overall, the trainability of maximum sprint workouts should be questioned from technical and metabolic points of view, especially as they are usually performed at submaximal efforts. Just like resistance training is an interesting tool for the acceleration phase, assistance training is theoretically suited to develop maximum velocity. However, while there is already a body of literature regarding cohorts of sprinters using "overspeed" devices, the magnitude of the effect on running technique at an individual level over time on elite athletes is yet to be clarified.

<u>Speed maintenance</u>

In London, the world champion Tori Bowie showed the best speed maintenance – while she didn't have the highest top speed, she was the fastest for each 10 m intervals from 70 to 100 m (Table 2.1), and the difference between her last 10 m and her fastest 10 m of the race was the smallest (0.04 s). The ability to maintain a high percentage of the maximum speed has shown to be higher in the fastest groups of sprinters among all the participants to the 100 m competition at the 1996 OG and 1997 WC. In 3 of the 4 women's major finals where laser gun has been used, the gold medal was determined by speed maintenance rather than maximum speed: indeed, Gail Devers in Atlanta 1996, Marion Jones in Athens 1997 and Carmelita Jeter in Daegu 2011 (Ruy, 2011) had lower top speed than Merlene Ottey, Zhanna Pintusevich and Veronica Campbell-Brown in their respective finals, but managed to beat them thanks to a longer distance run at 98% or more of their top speed. Therefore, Devers, Jones and Jeter covered 38 m, 42 m and 39 m, respectively, at this intensity, which is comparable to what Usain Bolt did (38 m) when he set the current men's 100 m world record in 9.58 s in 2009.

However in Osaka 2007, maximum speed was associated with 100 m time rather than deceleration in women (Saito, 2008) and rate of decrease in speed had a small effect on the final time but affected the ranking in each race (Matsuo, 2010a). Even though it was again the case in London, more systematic research needs to be done in this area. Much has been said about women's world record holder Florence Griffith-Joyner who maintained her fastest 10 m split (0.91 s) from 60 to 90 m and lost only 0.01 s in the final 10 m while celebrating her victory in Seoul 1988 final. However, some athletes possessing this extraordinary ability early in their career managed to improve their 100 m personal best by losing it and by increasing their acceleration and top speed. It was the case for 1983 and 1987 100 m world champions Marlies Göhr and Silke Gladisch – as teenagers they covered the last 20 m of their race (11.17 s in 1976 and 11.33 s in 1982, respectively) at 97.5% and 100% of their top speed, while during their lifetime best races (10.81 s in 1983 and 10.86 s in 1987), they ran that section at 96.4% and 97.4%. By contrast, the 1991 world champion Katrin Krabbe ran the last 20 m section at 96.2% in 1986 for 11.49 s race, and improved her speed endurance to 97.3% in 1990 for 10.89 s. Such career follow-ups are very rare and only available for these three world champions from East Germany, so more data is needed to evaluate longitudinal progression of athletes.

Again, these data have implications for coaching. Distances usually used in flying runs to work top speed (all out efforts over 20 to 30 m with a run-up of 20 to 30 m) might be too short to effectively challenge the metabolic and neuromuscular systems while trying to sprint with a proper relaxation. While this might be more suited to lower national-class female athletes, coaches should keep in mind that elite female sprinters might benefit from using longer run-up and longer all-out effort, up to 40 m each. Emphasis must be put on relaxation, in order to reduce the proportion of muscular activation during strides, economising metabolic energy, and to promote a higher rate of force development during ground contact as well as longer steps.

Towards the individualisation of training

Like men, elite female sprinters display a variety of body sizes, movement characteristics and physical abilities. Long time has passed since the Soviet models on physical abilities, as today's sprinters' features are in such a range that some are overlapping those of some elite men, and some other would be characteristic of regional class female athletes. For sure the era of "models" is long past and training must be individualised. All the finalists in London fell within this large range for sprinters at 11.00 s or faster (analysis for lifetime best races of 91 female sprinters under 11 s and training data for 42 of them):

Parameter	Mean	Minimum	Maximum
Body height (m)	1.68	1.55 (SA. Fraser, 10.70 s, 2012)	1.82 (H. Drechsler, 10.91 s, 1986)
Body mass (kg)	59	50 (M. Lee, 10.85 s, 2008)	71 (C. Arron, 10.73 s, 1998)
Step length (m)	2.05	1.84 (M. Göhr, 10.81 s, 1983)	2.34 (MJ. Pérec, 10.96 s, 1991)
Relative step length	1.218	1.08 (B Wöckel, 10.95 s, 1982)	1.33 (G. Devers, 10.82, 1993)
Step rate (Hz)	4.50	3.91 (MJ. Pérec, 10.96 s, 1991)	5.01 (M. Göhr, 10.81 s, 1983)
300 m training (s)	36.00	39.00	34.1
Standing long jump (m)	2.95	2.58	3.43
Standing triple jump (m)	8.40	6.84	9.70
Shot throw forward (m)	15.50	13.30	19.00
Shot throw backward (m)	16.50	14.20	19.65
Squat (kg)	150	90	220
Bench press (kg)	80	45	100
Cleans (kg)	75	50	100

The influence of physical abilities and anthropometric markers on these sprinting step parameters for elite women in still unclear. Leg length is known to be a determinant of step length (Hoffmann, 1967 on 23 female sprinters including Olympic champions of the 1960s), but deeper study was made in East Germany in 1980 on the national team which included 10 world record holders in sprints and relays and 3 sub-11 s sprinters (Erdmann, 1981). Longer steps were associated with longer foot length excluding toes, longer foot height, and a smaller foot lever ratio (ratio between foot length excluding toes and heel length) which allows a good conversion of the applied muscle power. Higher step frequency was associated with smaller feet dimensions, smaller thigh length, and smaller calf circumference, which all mechanically contribute to reduce inertia moment, through a lighter system with a smaller radius of gyration and a higher rotation velocity. According to these parameters, sprinters must be either step length or frequency emphasised and be trained more towards higher rate of movement or higher force application in order to find the optimal ratios. Research must be done to try to duplicate these results with contemporary athletes of various level of performance.

Another method for training individualisation is to observe the changes in step parameters with the progression of sprint results to assess if the sprinter was improving mainly due step length or frequency increment, or both. Such work was done in Soviet Union (Levchenko, 1988), giving orientation towards the athlete's natural inclination to run with a certain structure. In London's 2017 final, Ta Lou was the only one to run at her personal best level. For all the others, the loss of speed was explained by reduction of step length in 5 cases and by step frequency in 2 cases.

	Time (s)		Step length (m)		Step frequency (Hz)	
	PB	**WC 2017**	**PB**	**WC 2017**	**PB**	**WC 2017**
BOWIE	10.78	10.85	2.18	2.11	4.26	4.38
TA LOU	10.86	10.86	2.01	2.01	4.58	4.58
SCHIPPERS	10.81	10.96	2.14	2.11	4.32	4.32
AHOURÉ	10.78	10.98	1.99	1.91	4.67	4.77
THOMPSON	10.70	10.98	2.04	1.98	4.57	4.61
AHYE	10.82	11.01	1.99	1.98	4.64	4.58
SANTOS	10.96	11.06	1.96	1.97	4.64	4.59
BAPTISTE	10.83	11.09	2.01	1.96	4.59	4.60

However, comparing the progression of these athletes when they were not yet at world class level ("Early") shows that they improved mostly by increasing step frequency.

	Age	Time (s)		Step length (m)		Step frequency (Hz)	
		Early	PB	Early	PB	Early	PB
BOWIE	21/25	11.30	10.78	2.19	2.18	4.04	4.26
TA LOU	23/28	11.53	10.86	1.98	2.01	4.37	4.58
SCHIPPERS	19/23	11.56	10.81	2.08	2.14	4.15	4.32
AHOURÉ				***No data***			
THOMPSON	21/24	11.49	10.70	2.03	2.04	4.29	4.57
AHYE	20/25	11.32	10.82	2.00	1.99	4.41	4.64
SANTOS	16/26	11.44	10.96	2.00	1.96	4.38	4.64
BAPTISTE				***No data***			

Much more data is needed to confirm if this trend is general, but by no means should it be interpreted as a model. Indeed, the past 6 world record holders at 100 m had different career paths: Renate Stecher (GDR, 11.07 s in 1972), Inge Helten (FRG, 11.04 s in 1976), Marlies Göhr (GDR, 10.81 s in 1983) and Evelyn Ashford (USA, 10.76 s in 1984) were step frequency reliant, whilst Annegret Richter (FRG, 11.01 s in 1976) and Florence Griffith-Joyner (USA, 10.49 s in 1988) mostly improved their running speed through longer steps.

While men and women compete in different categories, it is now common practice that women train with men. Thus, coaches now have direct comparisons between them, but it is important to consider that elite women are not comparable to "slower men" as some of their features match some of those of elite men. The kinematic analysis in London 2017 confirmed that there is an overlap in some parameters between genders, and while the main difference in running speed is attributed to step length, when compared to body height, the difference disappears – the mean relative step length for sub-11 s female sprinters is 1.218, very close to what is found in men (1.223). As step length and frequency are both the product of strength expression on the track at high speed, it is interesting to look at the strength level of the athletes in isolation from the running movement. On average, elite female sprinters have much less static strength than elite male sprinters and regional class males that have same sprint records as elite females; the difference gets reduced when static strength is divided by body mass (relative strength). Finally, there is virtually no difference in start-strength (expressed in the force reached after 0.1 s of muscular activation) between elite male and female sprinters, both groups being significantly better than the regional class males (cf Letzelter, 1973, 1974, studies that included some 1972 Olympic finalists).

More research needs to be done to understand the interplay between phenotypic traits (body composition, muscle fibre type distribution and limb dimensions), running technique (kinematic parameters, direction of force application and emphasis on relaxation), physical abilities (rate of force development and rate of muscular relaxation) and their dynamic during the athlete's progression. These new findings will help the coaches to take in account these parameters in order to come up with truly individualised training based on a scientific approach.

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Coaching commentary – Ralph Mouchbahani

From the data collected, the current technical model used in the IAAF coach education programmes for sprint events is being confirmed. To be able to generate great velocities, it is of importance to master active ground preparation mechanics (sometimes describes as front side mechanics). Recovery mechanics are also of great importance, which can be shown through a quick heel recovery under the centre of mass and supported by an active knee drive. Finally, the transition from recovery to front side mechanics is crucial to support the driving force expressed in cycle velocities.

During acceleration, an accelerated push action is very important to drive the centre of mass. This is expressed through low heel recovery and active knee drive complimenting hip extension. In the high-velocity phase, small inter-thigh angles generate greater velocities. Further, a faster stride cycle and a focus on a tall sprinting posture can positively affect performance at top speeds. This is reflected in greater hip, knee and ankle angles at touchdown and little differences in angles at toe-off. Hence, greater horizontal velocities can be generated for the centre of mass. Smaller braking forces at touchdown occur to maintain the horizontal velocity of the centre of mass.

The data also clearly reflects the transition mechanics from: (1) start/acceleration to top velocity and (2) top velocity to maintenance phase, must be mastered from a technical perspective to be able to finish the race with as little velocity loss as possible.

Recommendations for practice

1. Drills for acceleration

- Push should be initiated through the hip extensors and not by knee extension. The sequence order of joints is hip-knee-ankle to toe-off.
- Low heel, active knee and mainly focus on push-push faster into shoulder-hip alignment.

2. Transition drills to prepare an active knee

- Quick heel recovery (small inter-thigh angle) under the hip extensors.
- Active knee drive for smooth and effective ground preparation (step over drills).

3. High velocity drills

- Step over drills to prepare activity and high sped at touchdown and through the ground. How many drills are done is of less importance. More important is that execution meets quality and progressing to more complex drills by combining various drills into one movement time and movement pattern that are congruent with the technical model.

- Drills:
    - Single leg bounds – speed bounds.
    - Straight leg shuffle into sprinting.
    - Single leg step over ankle, calf, knee.
    - Quick butt-touch underneath.
    - Step over.

CONTRIBUTORS

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Ralph Mouchbahani is a global master in implementing sport structures for federations within a high-performance environment. He is an editor of the IAAF Coaches Education and Certification System and a senior IAAF and DOSB lecturer with exceptional athletic technical knowledge and a passion for sport research. In his career, he has coached many elite athletes, including sprinters, helping them to achieve podium performances at several international competitions. Ralph is managing partner in Athletic-Solutions, a company that focuses on bringing Sport Science and Practice together to help coaches maximise their efforts.

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