



# BIOMECHANICAL REPORT

FOR THE

*IAAF World Championships*  
**LONDON 2017**

**100 m Men's**

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## INTRODUCTION

The men's 100 m final and semi-finals took place on the night of August 5<sup>th</sup> in good weather conditions. There was great excitement coming into the event given that this was Usain Bolt's last ever individual competitive race. Coming into the race, Christian Coleman of the USA was the favourite having recorded the fastest time in 2017 and qualifying first from his semi-final. Despite this and leading the way throughout the race, Christian Coleman eventually had to settle for the silver medal. Justin Gatlin's late surge was enough to ensure he pipped Coleman by a mere 0.02 seconds to clinch gold and make it a 1-2 for the USA. Usain Bolt finished a further 0.01 seconds further back from Coleman to take the bronze medal despite a slow start. There were season's bests for the gold and bronze medallists.

RECORDS	RESULT NAME	COUNTRY	AGE	VENUE	DATE
World Record <b>WR</b>	9.58 Usain BOLT	JAM	23	Berlin (Olympiastadion)	16 Aug 2009
Championships Record <b>CR</b>	9.58 Usain BOLT	JAM	23	Berlin (Olympiastadion)	16 Aug 2009
World Leading <b>WL</b>	9.82 Christian COLEMAN	USA	21	Eugene (Hayward Field), OR	7 Jun 2017
Area Record <b>AR</b>	National Record <b>NR</b>	Personal Best <b>PB</b>	Season Best <b>SB</b>		

5 August 2017 21:46 START TIME 19° C TEMPERATURE 49 % HUMIDITY -0.8 m/s WIND

PLACE	NAME	COUNTRY	DATE OF BIRTH	LANE	RESULT	REACTION	Fn
1	Justin GATLIN	USA	10 Feb 82	8	9.92	SB	0.138
2	Christian COLEMAN	USA	6 Mar 96	5	9.94		0.123
3	Usain BOLT	JAM	21 Aug 86	4	9.95	SB	0.183
4	Yohan BLAKE	JAM	26 Dec 89	7	9.99		0.137
5	Akani SIMBINE	RSA	21 Sep 93	6	10.01		0.141
6	Jimmy VICAUT	FRA	27 Feb 92	3	10.08		0.152
7	Reece PRESCOD	GBR	29 Feb 96	9	10.17		0.145
8	Bingtian SU	CHN	29 Aug 89	2	10.27		0.224

Timing and Measurement by SEIKO AT-100-M-f--1--.RS1..v1 Issued at 21:48 on Saturday, 05 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).

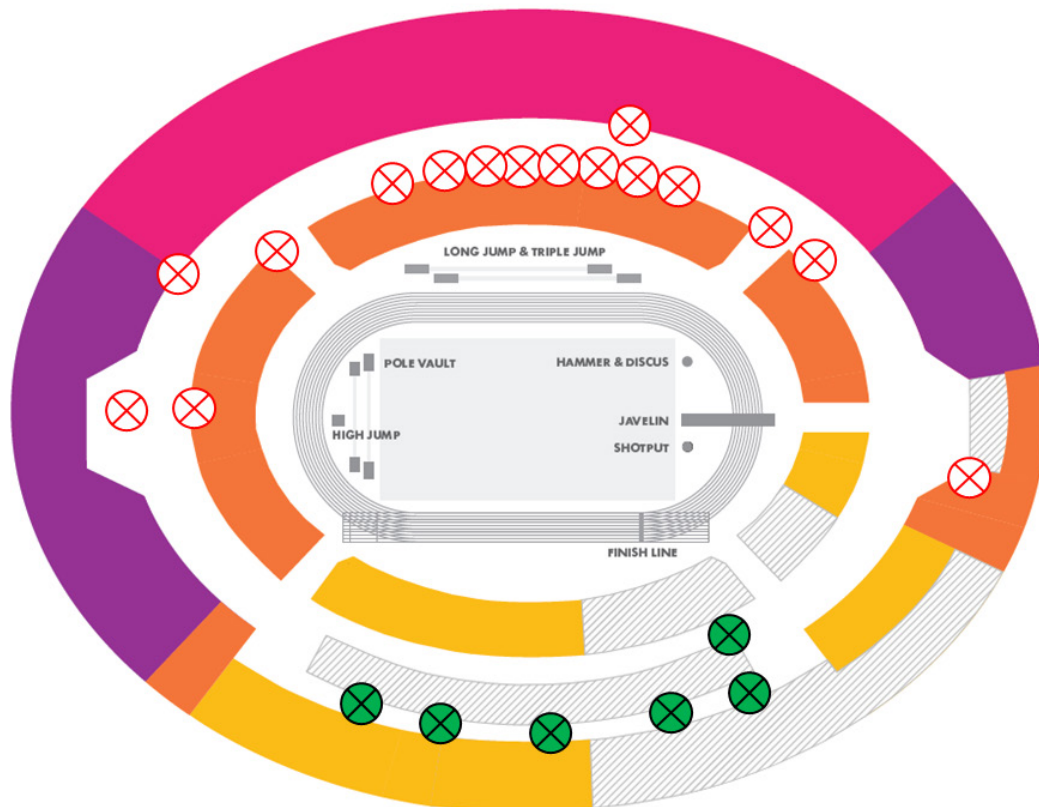


Figure 1. Camera layout for the men's 100 m indicated by green in-filled circles.

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.

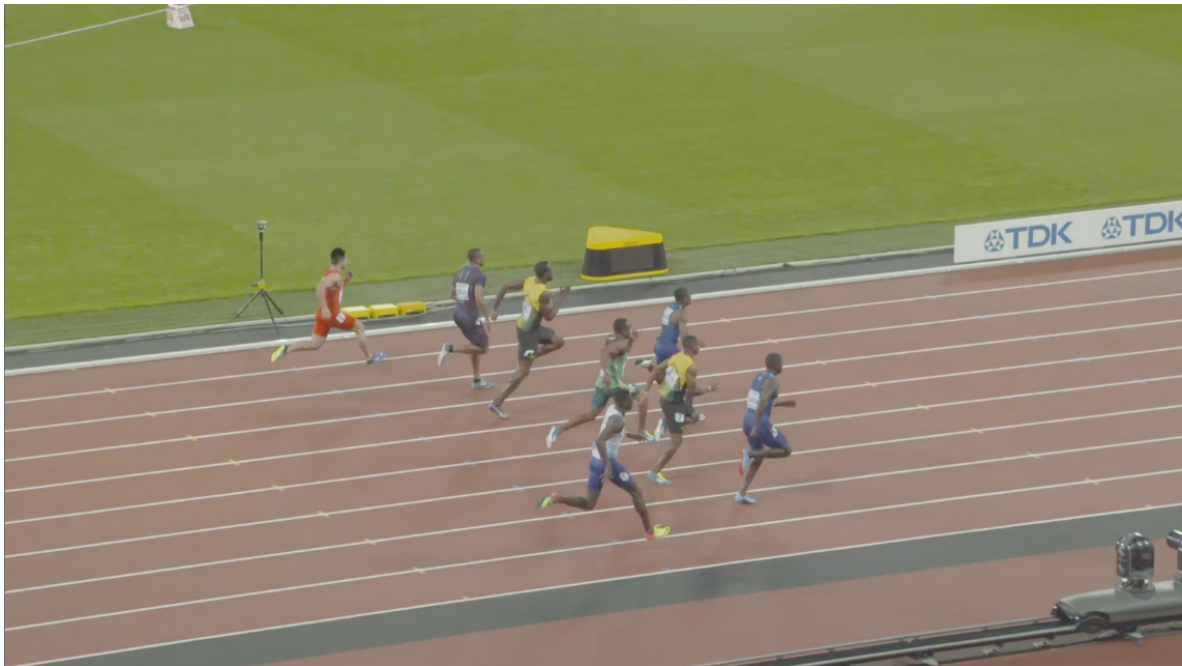


Figure 3. Action from the 100 m men's final.

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.

<b>Variable</b>	<b>Definition</b>
<b>Race position</b>	Ranking of each athlete in the race at each 10 m interval.
<b>Split time</b>	Time taken to complete each 10 m interval.
<b>Mean speed<sup>#</sup></b>	Mean speed throughout each 10 m interval based on split time.
<b>Step length</b>	The distance covered from toe-off on one foot to toe-off on the other foot.
<b>Relative step length</b>	Step length as a proportion of the athlete's height (body height = 1.00).
<b>Step rate</b>	The number of steps per second (Hz).
<b>Step width</b>	Mediolateral distance between two consecutive foot contacts (foot tips).
<b>Contact time</b>	The time the foot is in contact with the ground.
<b>Flight time</b>	The time from toe-off (TO) of one foot to touchdown (TD) of the other foot.
<b>Step time</b>	Contact time + flight time.
<b>Step velocity<sup>#</sup></b>	Step length divided by step time.
<b>CM horizontal velocity<sup>#</sup></b>	Mean horizontal CM velocity over one step.
<b>Swing time</b>	The time that the foot is not in contact with the ground during one full stride.
<b>DCM TD</b>	The horizontal distance between the ground contact point (foot tip) at TD and the CM.

<b>DCM TO</b>	The horizontal distance between the ground contact point (foot tip) at TO and the CM.
<b>CM contact distance</b>	The horizontal distance that the CM travelled during a single ground contact.
<b>Braking phase</b>	The time period of the downward phase of the CM during ground contact.
<b>Propulsive phase</b>	The time period of the upward phase of the CM during ground contact.
<b>Height CM</b>	Vertical distance between the CM and the running surface during ground contact.
<b>Vertical CM velocity</b>	The vertical component of the CM velocity during ground contact.
<b>Foot horizontal velocity</b>	The horizontal component of the foot CM velocity.
<b>Foot vertical velocity</b>	The vertical component of the foot CM velocity.
<b>Resultant foot swing velocity</b>	The resultant linear velocity of the foot CM during the swing phase.
<b>Trunk angle (<math>\alpha</math>)</b>	The angle of the trunk relative to the horizontal and considered to be $90^\circ$ in the upright position.
<b>Knee angle (<math>\beta</math>)</b>	The angle between the thigh and lower leg and considered to be $180^\circ$ in the anatomical standing position.
<b>Contact leg hip angle (<math>\gamma</math>)</b>	The shoulder-hip-knee angle of the contact side.
<b>Swing leg hip angle (<math>\delta</math>)</b>	The shoulder-hip-knee angle of the swing side. <b>Note:</b> angle taken at toe-off only.
<b>Contact thigh angle (<math>\epsilon</math>)</b>	The angle between the thigh of the contact leg and the vertical.

<b>Swing thigh angle (<math>\zeta</math>)</b>	The angle between the thigh of the swing leg and the vertical.
<b>Thigh separation angle (<math>\eta</math>)</b>	The angle between the thighs of the contact and swing legs. This has been calculated as the difference between $\varepsilon$ and $\zeta$ .
<b>Shank angle (<math>\theta</math>)</b>	The angle of the lower leg relative to the running surface and considered to be $90^\circ$ when the shank is perpendicular to the running surface.
<b>Ankle angle (<math>\iota</math>)</b>	The angle between the lower leg and the foot and considered to be $90^\circ$ in the anatomical standing position.
<b>Angular velocity (hip, knee, ankle)</b>	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.

*Please note that the results from this report supersede the results contained within the fast report published in August 2017. The results presented here have been derived from data extracted from all cameras involved in the recording and digitised fully to provide a more accurate analysis of performance.*

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## RESULTS – FINAL

The following section of results includes data from the men'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).

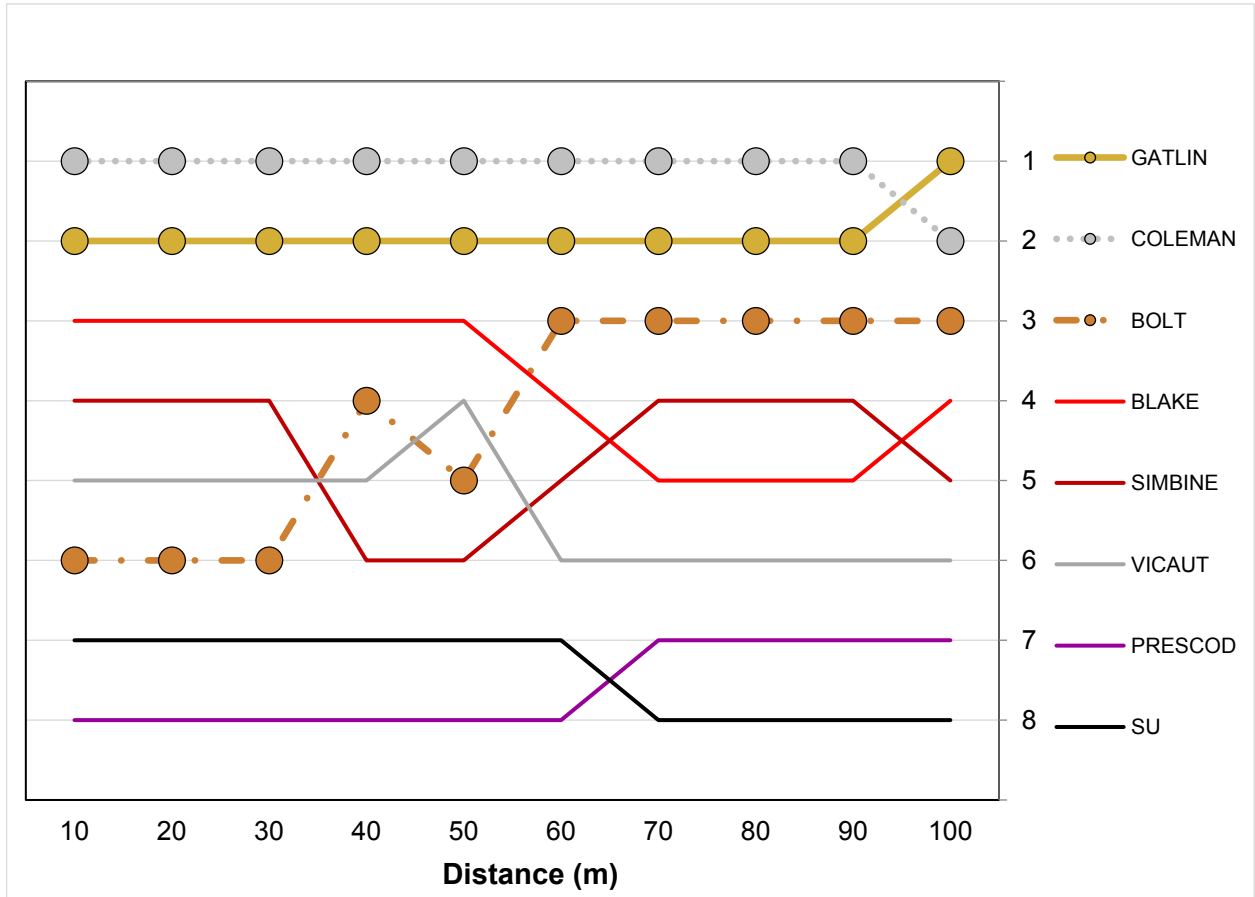


Figure 4. Race position of the finalists at each 10-metre split. Medallists have been highlighted in respective medallist colours.



## 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
<b>GATLIN</b>	0.138	1.88	1.02	0.91	0.90	0.88	0.86	0.86	0.87	0.87	0.87	9.92
<b>COLEMAN</b>	0.123	1.87	1.00	0.90	0.88	0.87	0.86	0.88	0.88	0.88	0.92	9.94
<b>BOLT</b>	0.183	1.96	1.02	0.90	0.88	0.88	0.85	0.85	0.86	0.86	0.89	9.95
<b>BLAKE</b>	0.137	1.89	1.03	0.91	0.90	0.89	0.88	0.87	0.88	0.87	0.87	9.99
<b>SIMBINE</b>	0.141	1.92	1.03	0.92	0.92	0.87	0.84	0.86	0.87	0.88	0.90	10.01
<b>VICAUT</b>	0.152	1.95	1.03	0.90	0.89	0.87	0.87	0.88	0.89	0.90	0.90	10.08
<b>PRESCOD</b>	0.145	2.04	1.05	0.92	0.92	0.89	0.86	0.86	0.87	0.88	0.88	10.17
<b>SU</b>	0.224	2.03	1.03	0.92	0.91	0.89	0.89	0.89	0.89	0.90	0.92	10.27

**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
<b>GATLIN</b>	0.138	1.88	2.90	3.81	4.71	5.59	6.45	7.31	8.18	9.05	9.92
<b>COLEMAN</b>	0.123	1.87	2.87	3.77	4.65	5.52	6.38	7.26	8.14	9.02	9.94
<b>BOLT</b>	0.183	1.96	2.98	3.88	4.76	5.64	6.49	7.34	8.20	9.06	9.95
<b>BLAKE</b>	0.137	1.89	2.92	3.83	4.73	5.62	6.50	7.37	8.25	9.12	9.99
<b>SIMBINE</b>	0.141	1.92	2.95	3.87	4.79	5.66	6.50	7.36	8.23	9.11	10.01
<b>VICAUT</b>	0.152	1.95	2.98	3.88	4.77	5.64	6.51	7.39	8.28	9.18	10.08
<b>PRESCOD</b>	0.145	2.04	3.09	4.01	4.93	5.82	6.68	7.54	8.41	9.29	10.17
<b>SU</b>	0.224	2.03	3.06	3.98	4.89	5.78	6.67	7.56	8.45	9.35	10.27

**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.

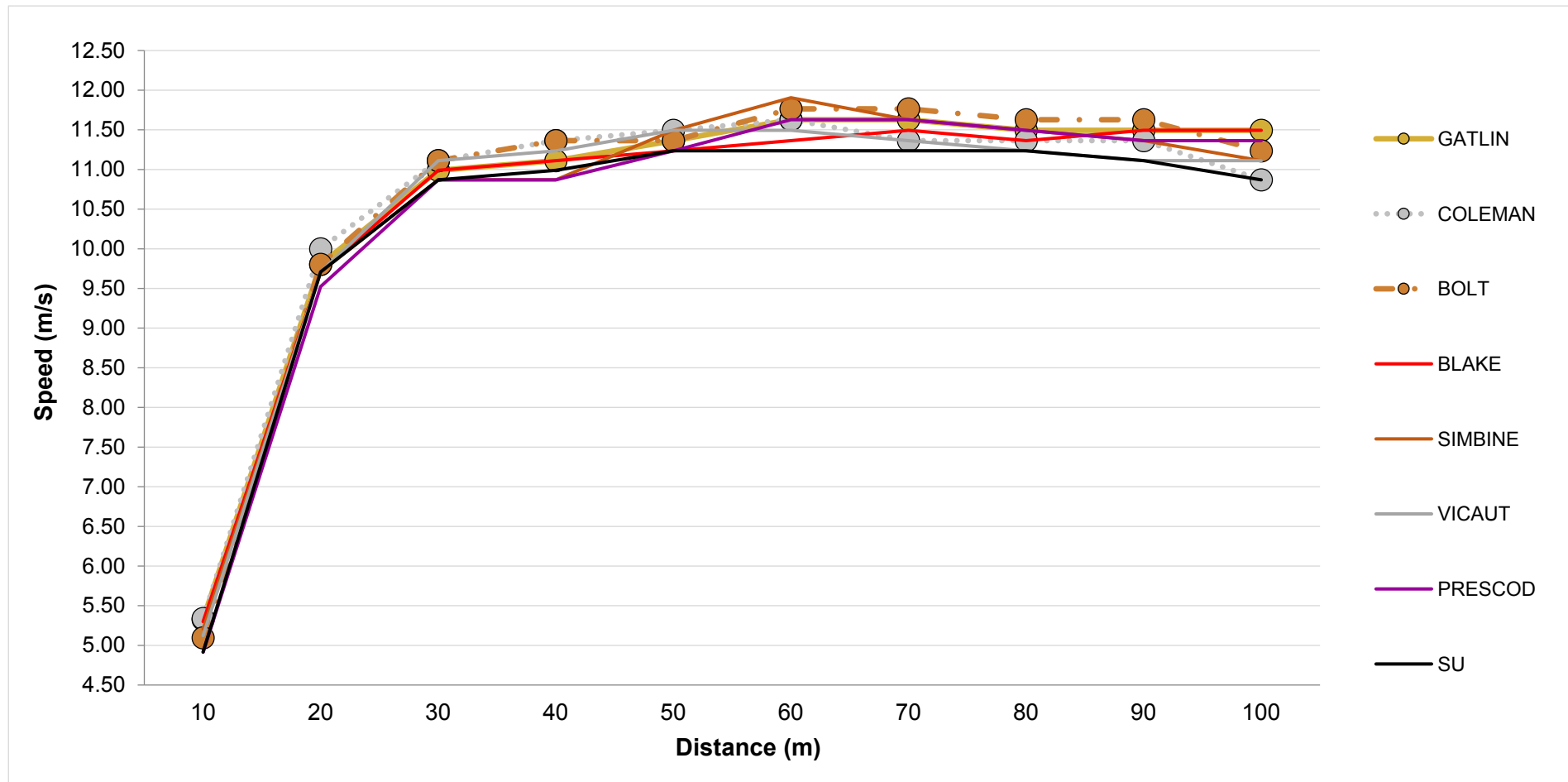


Figure 5. Mean speed over each 10-metre split.

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

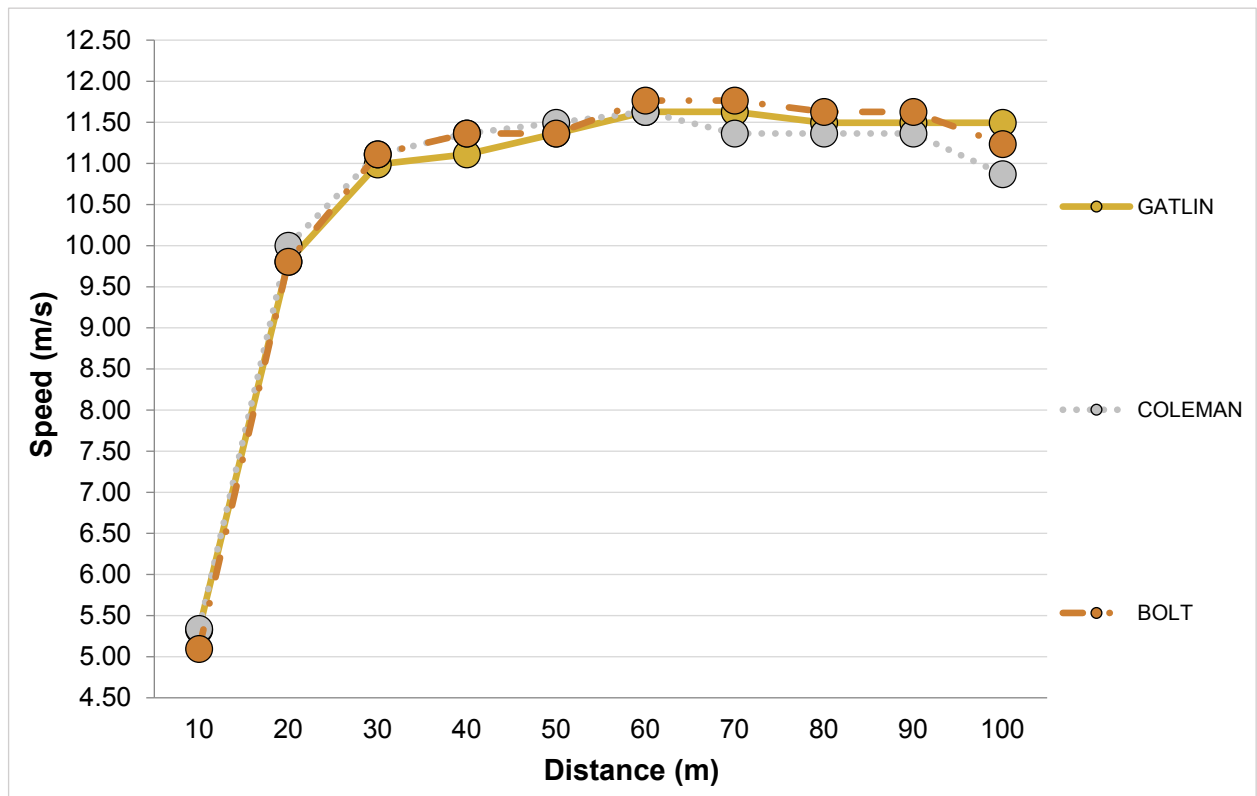


Figure 6. Mean speed over each 10-metre split – medallists only.

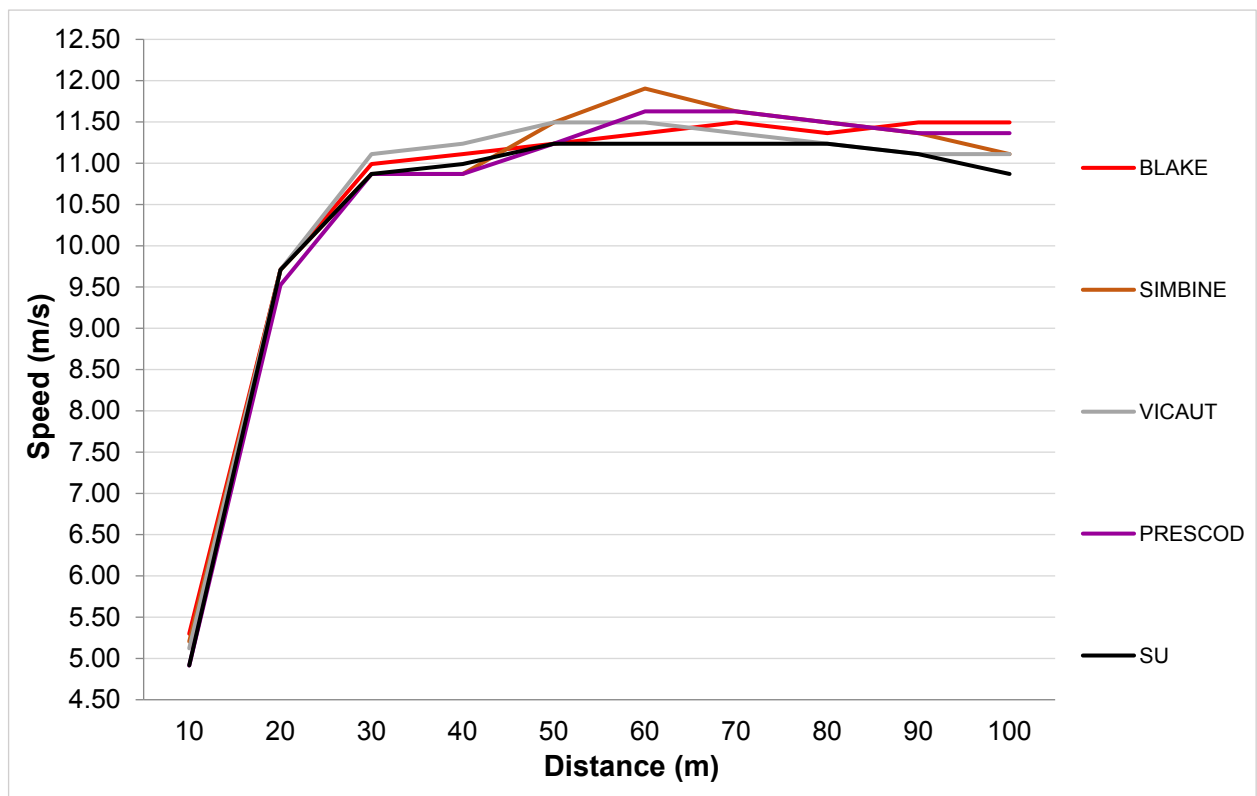


Figure 7. Mean speed over each 10-metre split – remaining five finalists.

## 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).

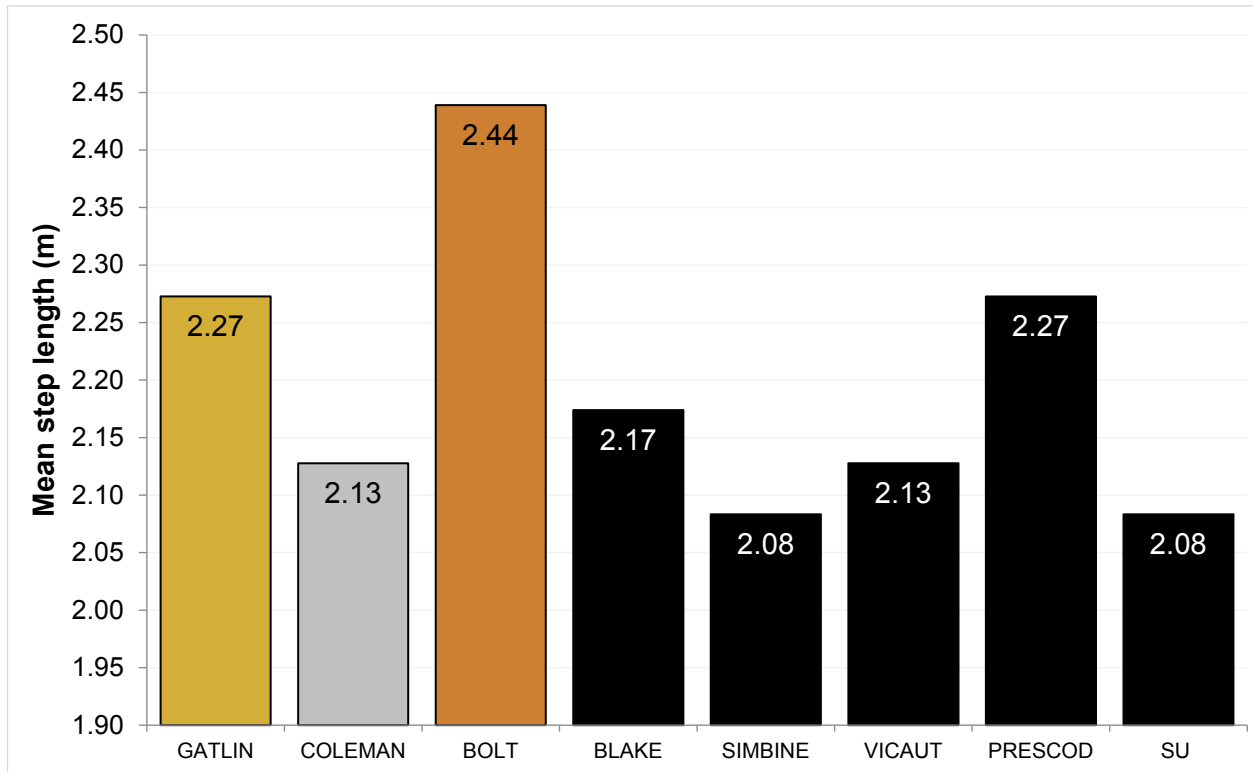


Figure 8. Mean absolute step length for each finalist over 100 metres.

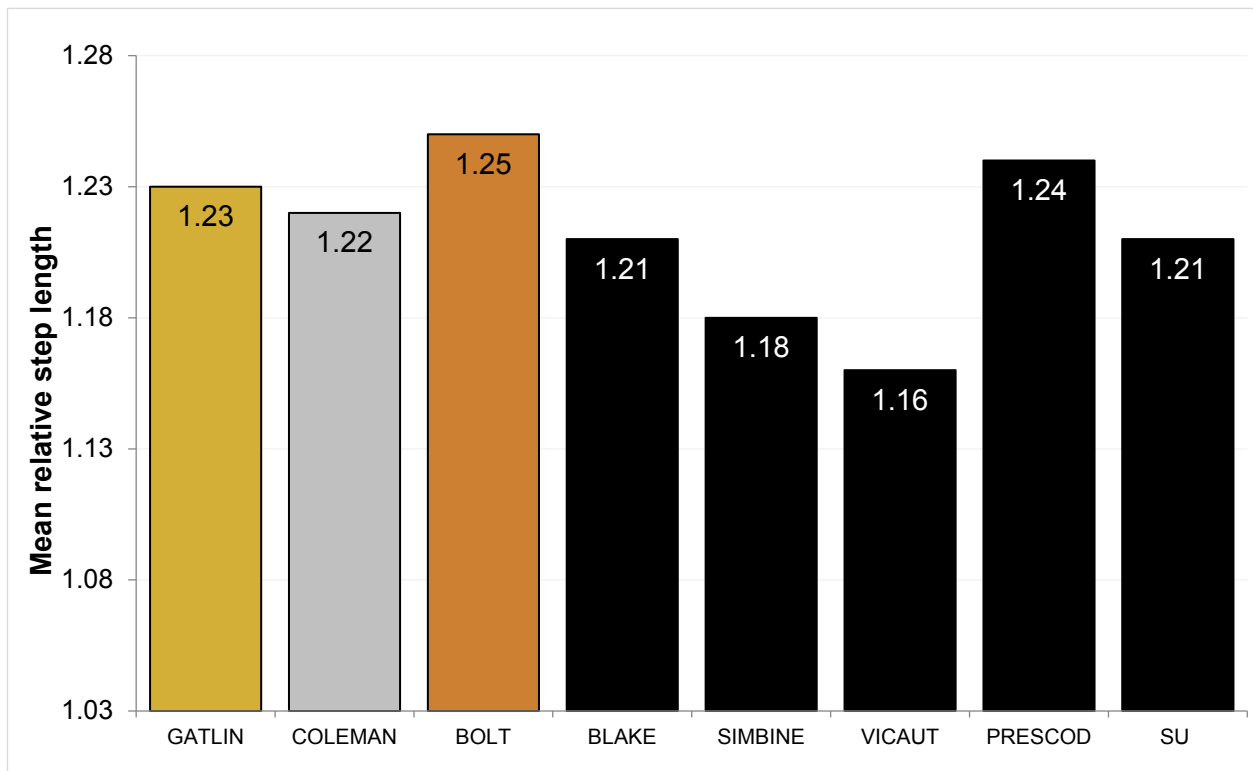


Figure 9. Mean relative step length for each finalist over 100 metres.

## Gold medallist profile

## JUSTIN GATLIN



Round	Time	vs. SB (23 <sup>rd</sup> June)	vs. PB (2015)	Notes
Final	9.92 s	-0.03 s	+0.18 s	New SB
		Final vs. Heat	Final vs. Semi-final	
Semi-final	10.09 s	-	-0.17 s	
Heat	10.05 s	-0.13 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)
<b>GATLIN</b>	2.51	1.36	4.67	0.12
<b>COLEMAN</b>	2.33	1.33	4.95	0.20
<b>BOLT</b>	2.70	1.38	4.39	0.15
<b>BLAKE</b>	2.38	1.32	4.85	0.23
<b>SIMBINE</b>	2.31	1.31	5.00	0.24
<b>VICAUT</b>	2.39	1.30	4.90	0.21
<b>PRESCOD</b>	2.51	1.36	4.63	0.22
<b>SU</b>	2.26	1.31	5.00	0.13

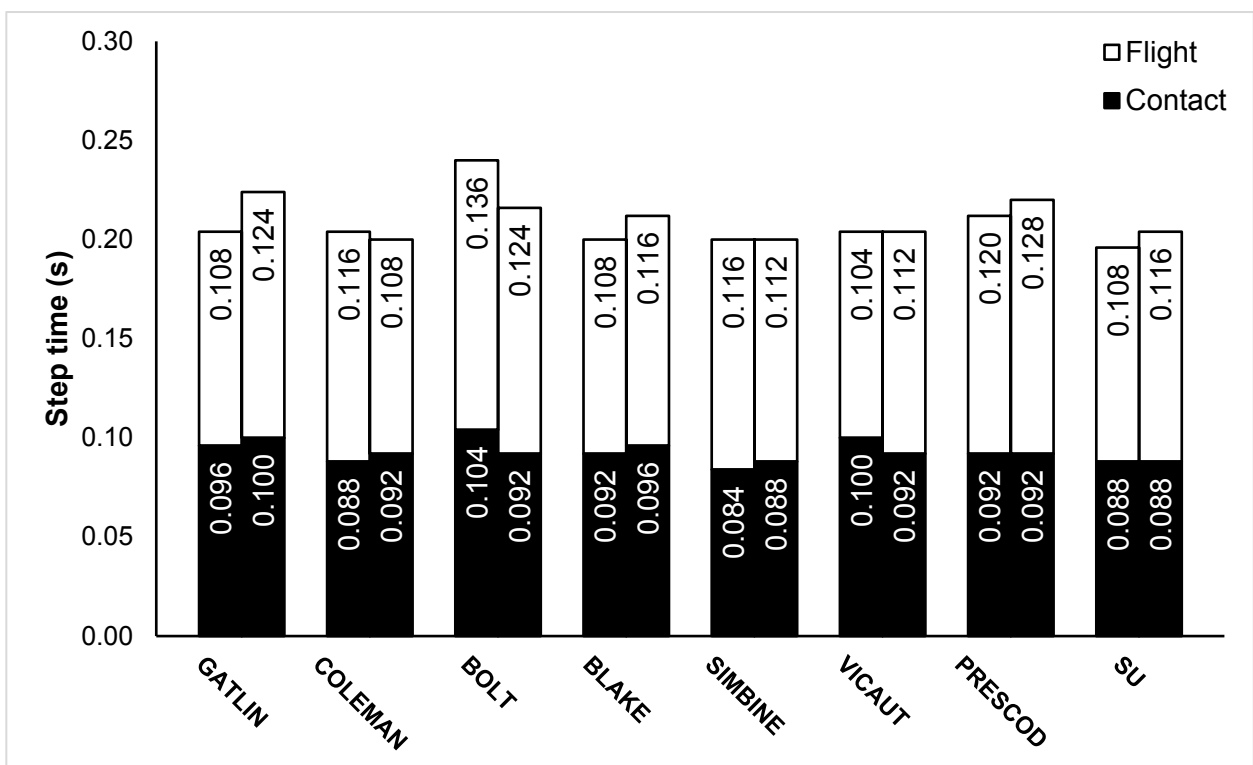


Figure 10. Contact, flight and step times during high velocity running for each finalist. Step time is the sum of contact and flight times. Left and right columns indicate left and right legs for each athlete, respectively.

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

	Step velocity (m/s)	CM horizontal velocity (m/s)
<b>GATLIN</b>	11.73	11.61
<b>COLEMAN</b>	11.53	11.66
<b>BOLT</b>	11.84	11.75
<b>BLAKE</b>	11.55	11.59
<b>SIMBINE</b>	11.55	11.62
<b>VICAUT</b>	11.72	11.54
<b>PRESCOD</b>	11.62	11.55
<b>SU</b>	11.30	11.35

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

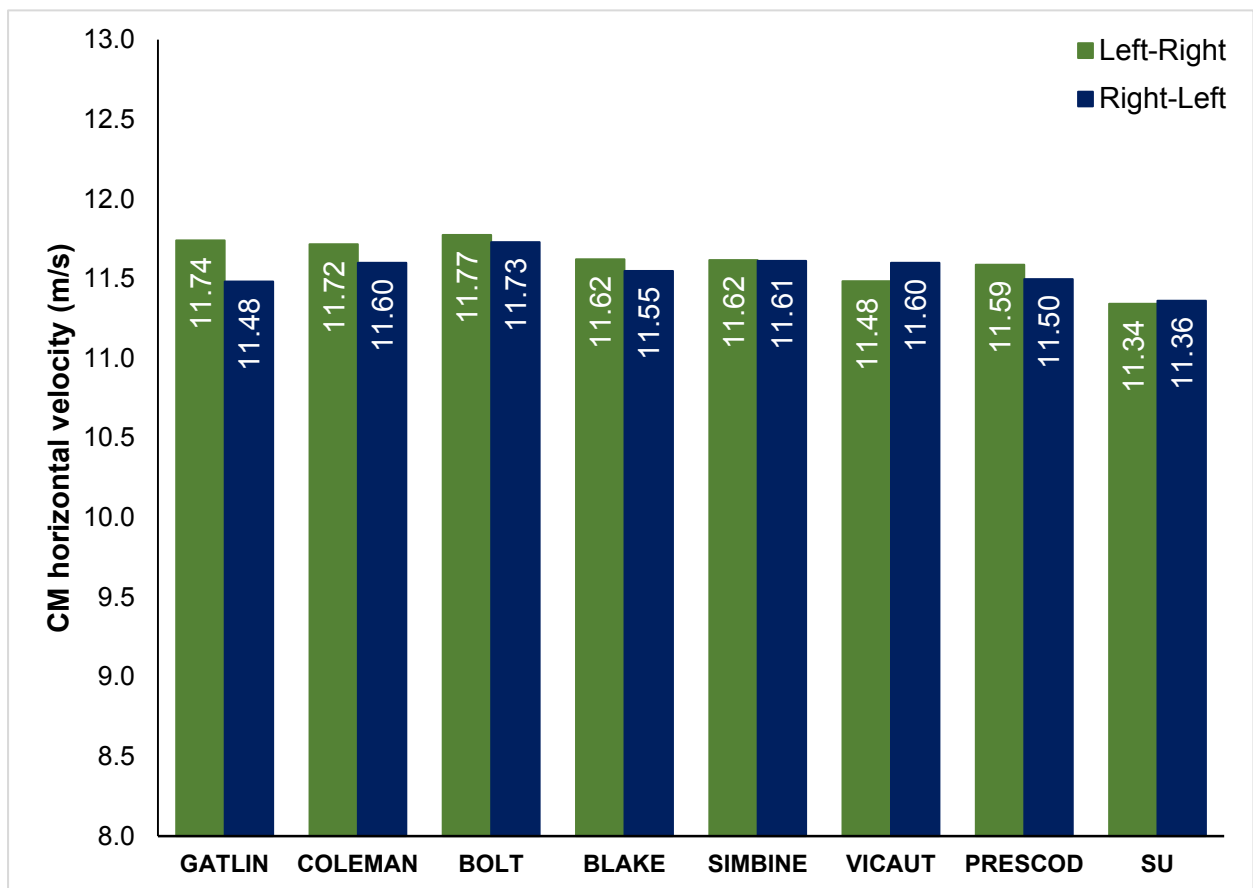


Figure 11. Individual centre of mass horizontal velocities for each digitised step.



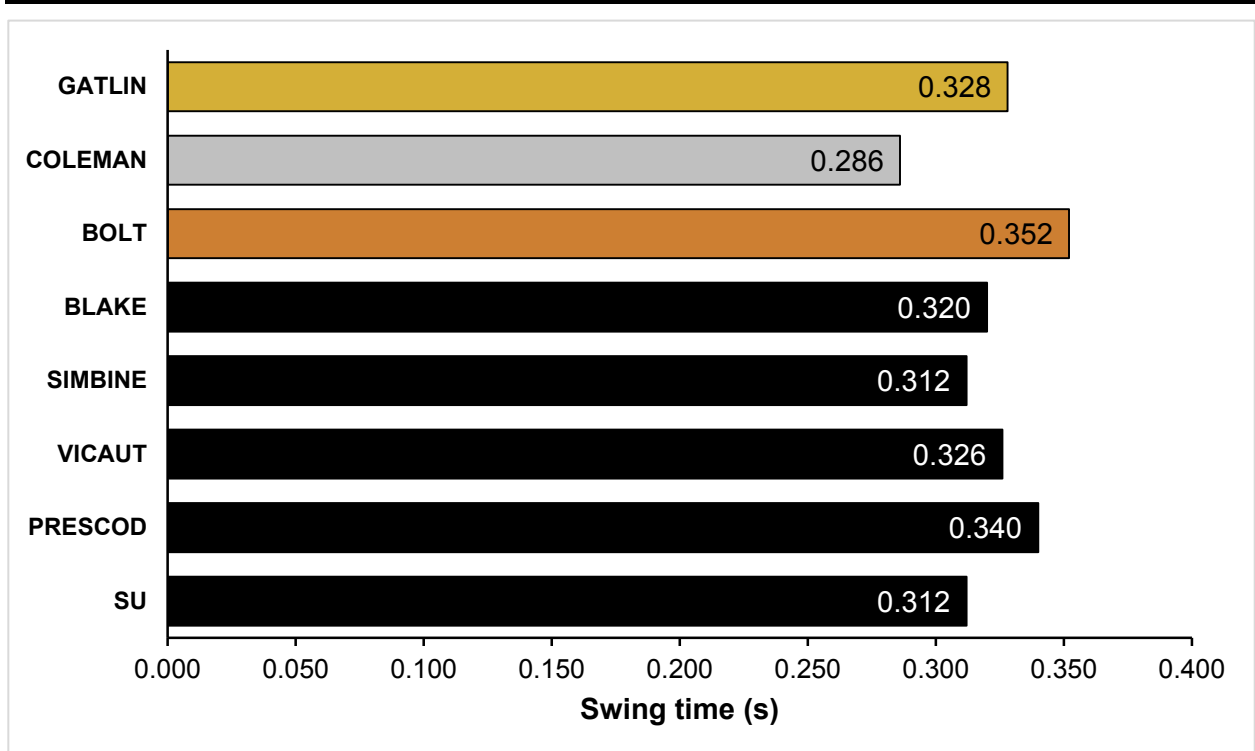


Figure 12. Swing time of one stride for each athlete. For some athletes, the stride was left-left contact, for some it was right-right contact.

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
<b>GATLIN</b>	0.48 / 26	0.40 / 22	0.65 / 35	0.63 / 34
<b>COLEMAN</b>	0.38 / 21	0.38 / 22	0.54 / 31	0.60 / 34
<b>BOLT</b>	0.48 / 25	0.32 / 16	0.67 / 35	0.68 / 35
<b>BLAKE</b>	0.33 / 18	0.33 / 18	0.67 / 37	0.63 / 35
<b>SIMBINE</b>	0.28 / 16	0.37 / 21	0.62 / 35	0.59 / 34
<b>VICAUT</b>	0.39 / 21	0.42 / 23	0.65 / 35	0.57 / 31
<b>PRESCOD</b>	0.33 / 18	0.43 / 23	0.65 / 35	0.60 / 33
<b>SU</b>	0.36 / 21	0.33 / 19	0.59 / 34	0.57 / 33

*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
<b>GATLIN</b>	1.13 / 61	1.03 / 56
<b>COLEMAN</b>	0.92 / 52	0.98 / 56
<b>BOLT</b>	1.15 / 60	1.00 / 51
<b>BLAKE</b>	1.00 / 55	0.96 / 53
<b>SIMBINE</b>	0.90 / 51	0.96 / 55
<b>VICAUT</b>	1.04 / 56	0.99 / 54
<b>PRESCOD</b>	0.98 / 53	1.03 / 56
<b>SU</b>	0.95 / 55	0.90 / 52

**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.

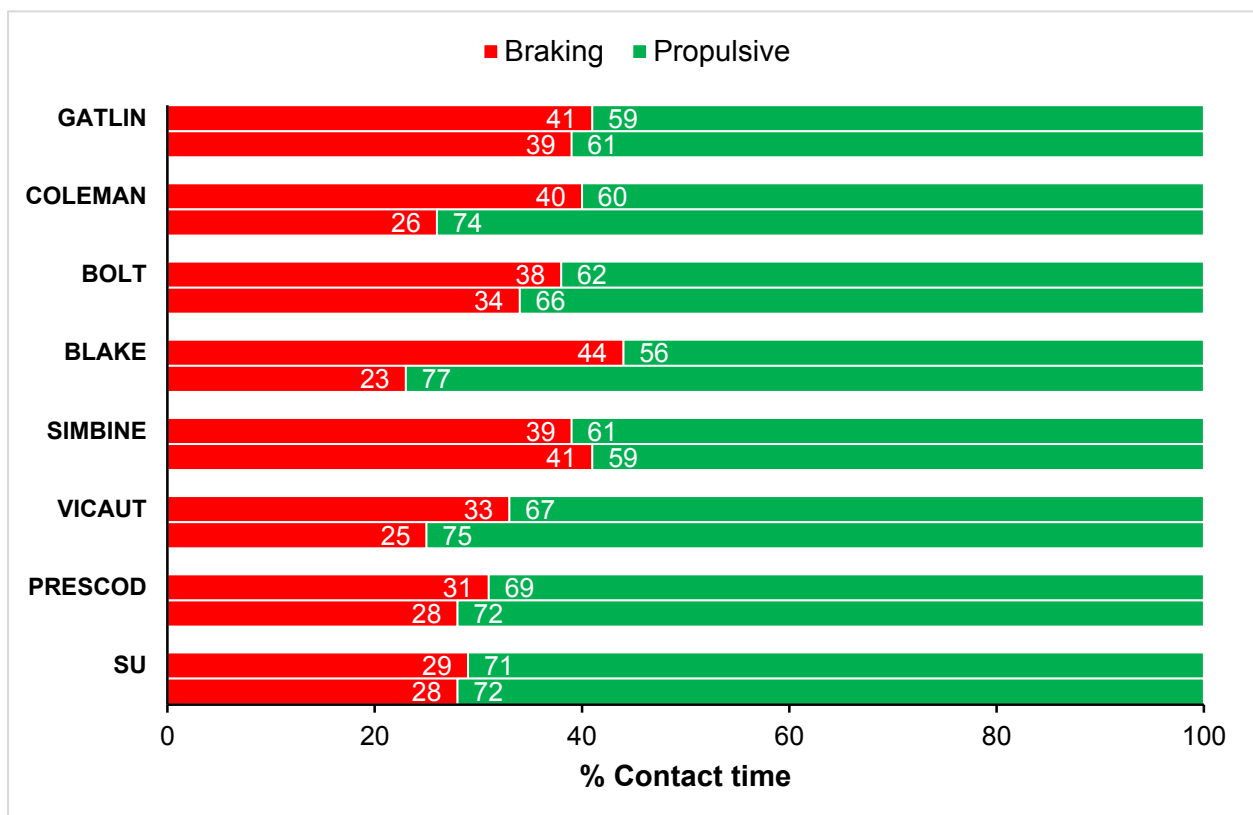


Figure 13. Relative proportions (%) of braking and propulsive phases during contact.

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%, 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).

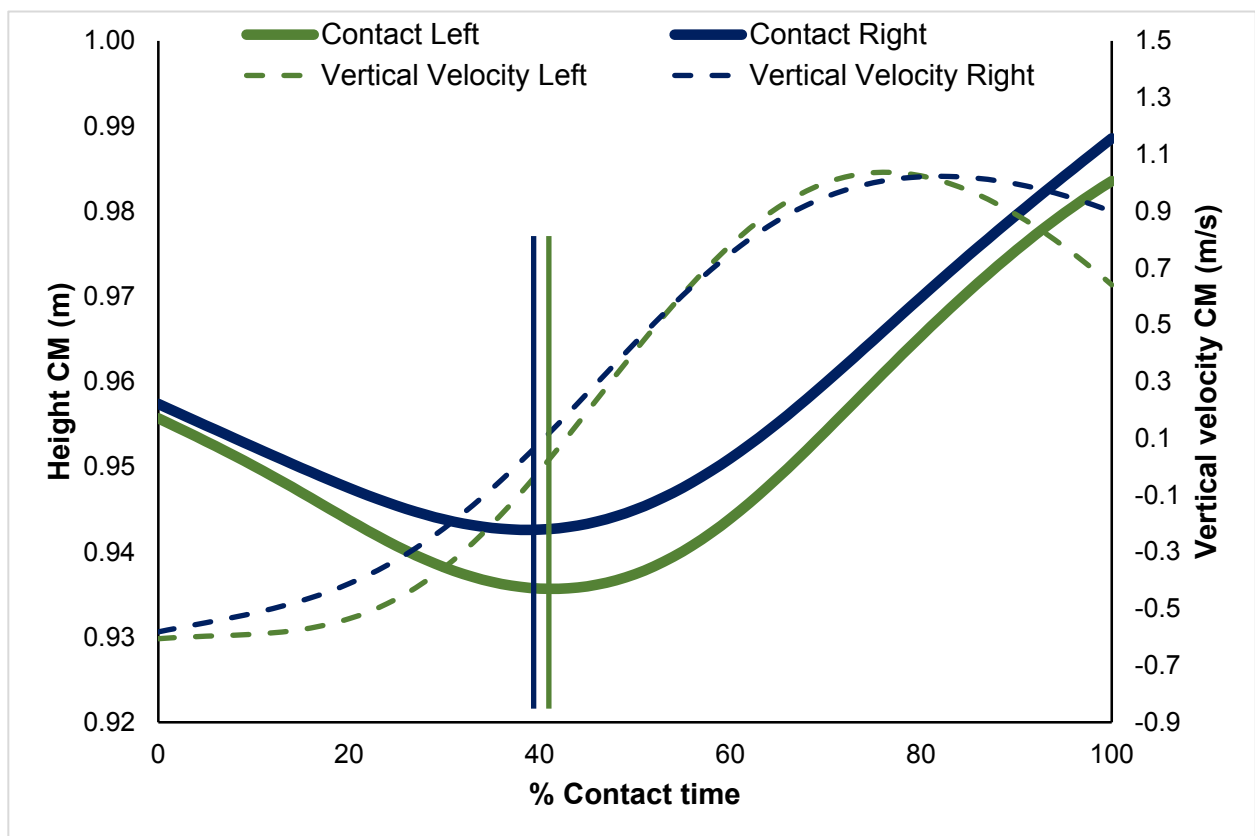


Figure 14.1. CM height and vertical CM velocity during left and right contacts for gold medallist Justin Gatlin.

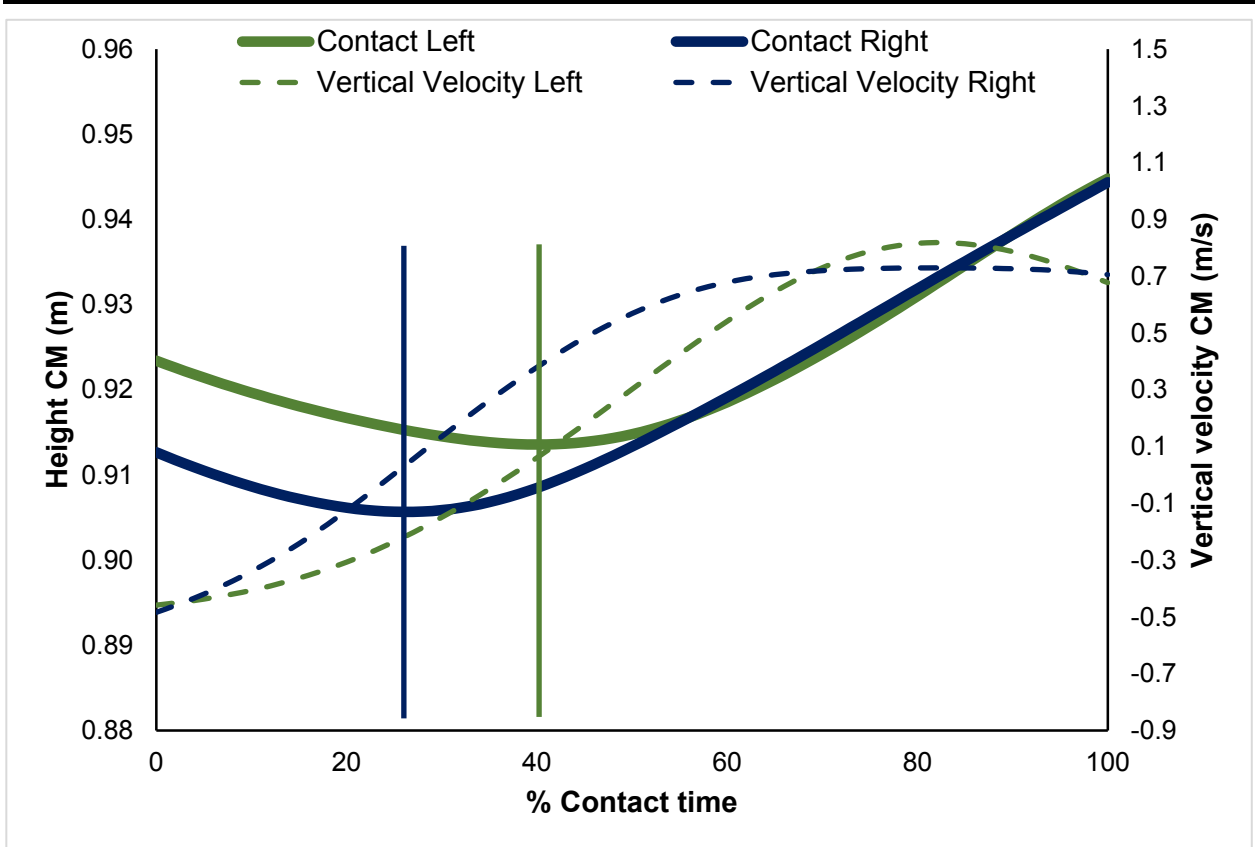


Figure 14.2. CM height and vertical CM velocity during left and right contacts for silver medallist Christian Coleman.

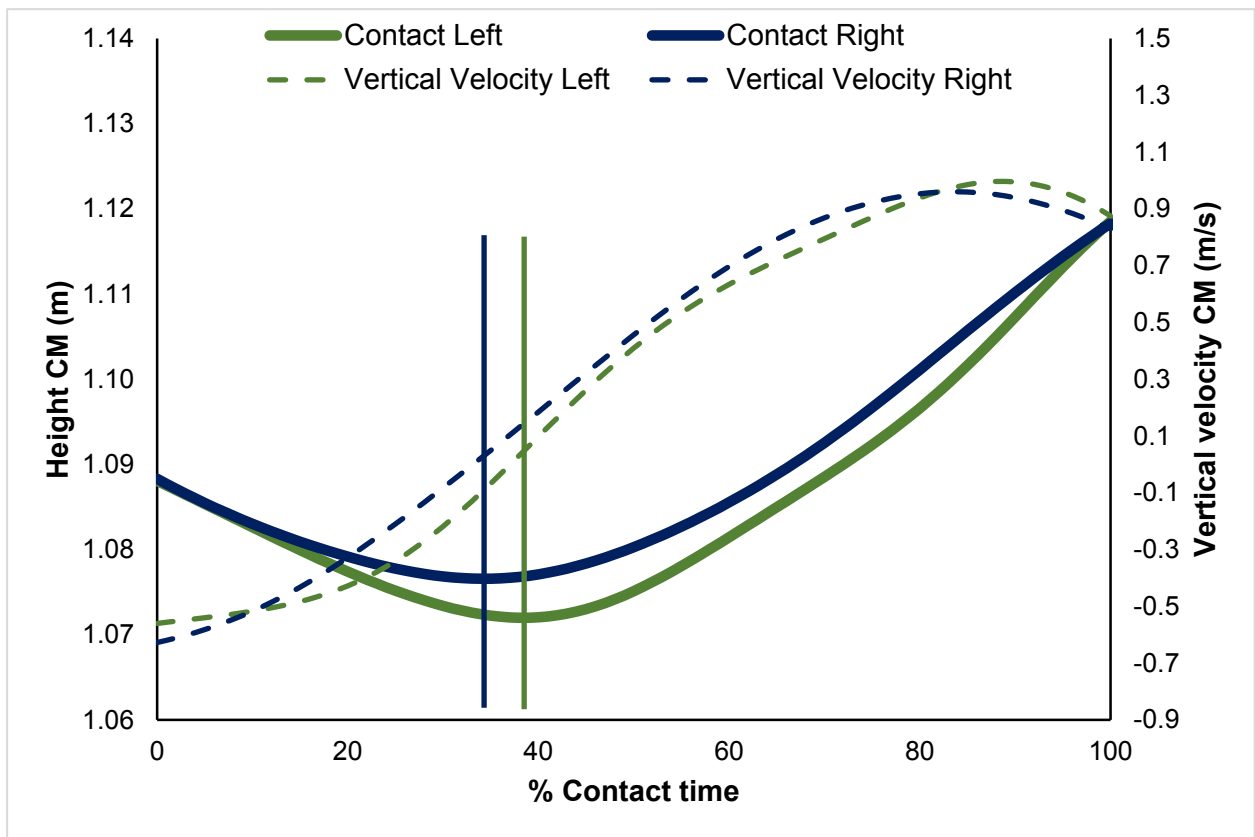


Figure 14.3. CM height and vertical CM velocity during left and right contacts for bronze medallist Usain Bolt.

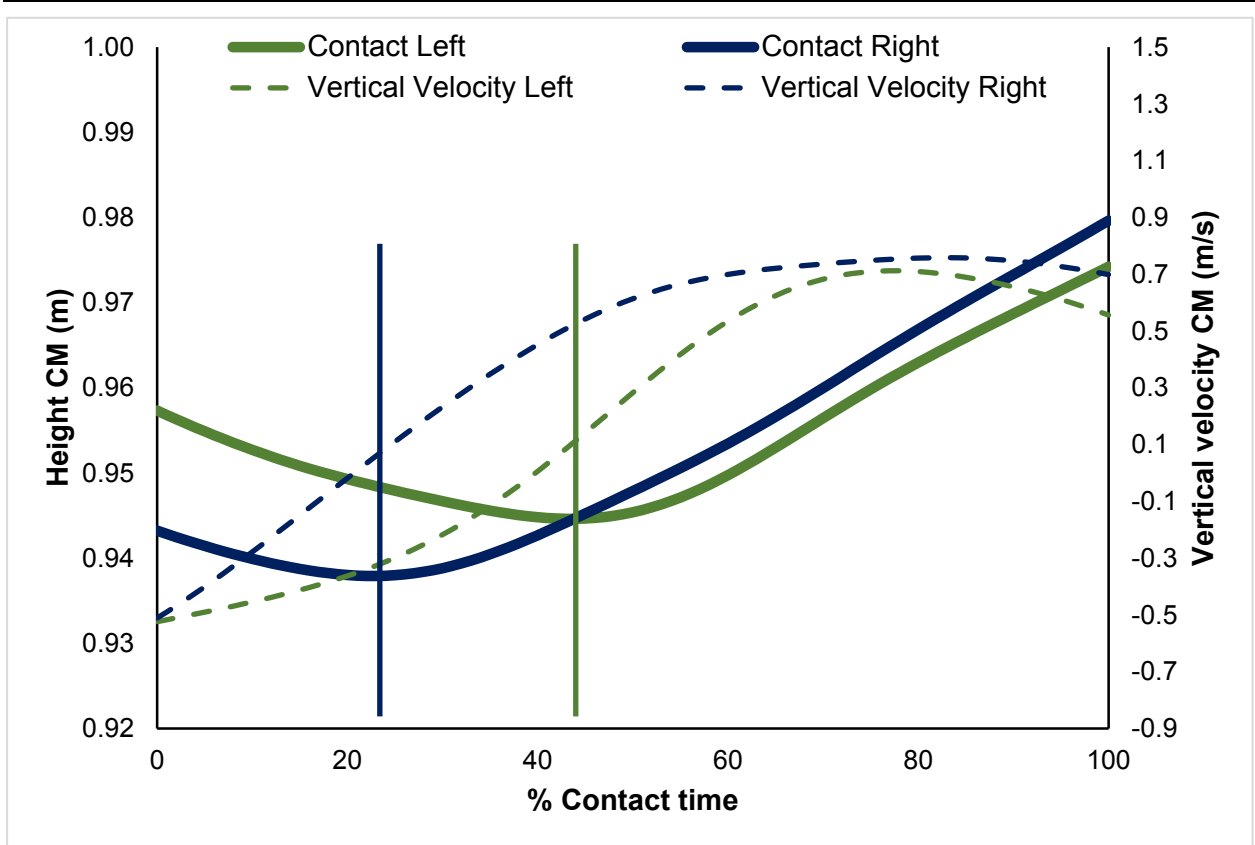


Figure 14.4. CM height and vertical CM velocity during left and right contacts for fourth placed Yohan Blake.

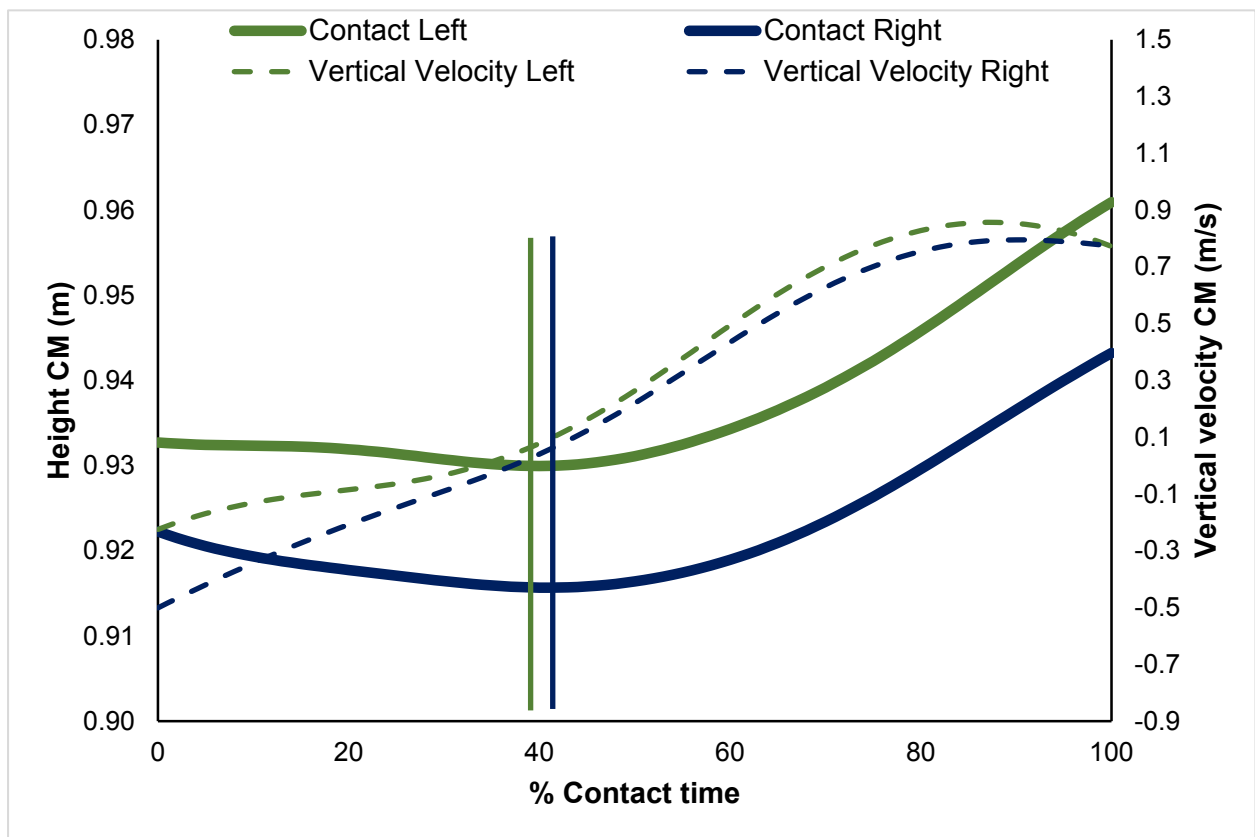


Figure 14.5. CM height and vertical CM velocity during left and right contacts for fifth placed Akani Simbine.

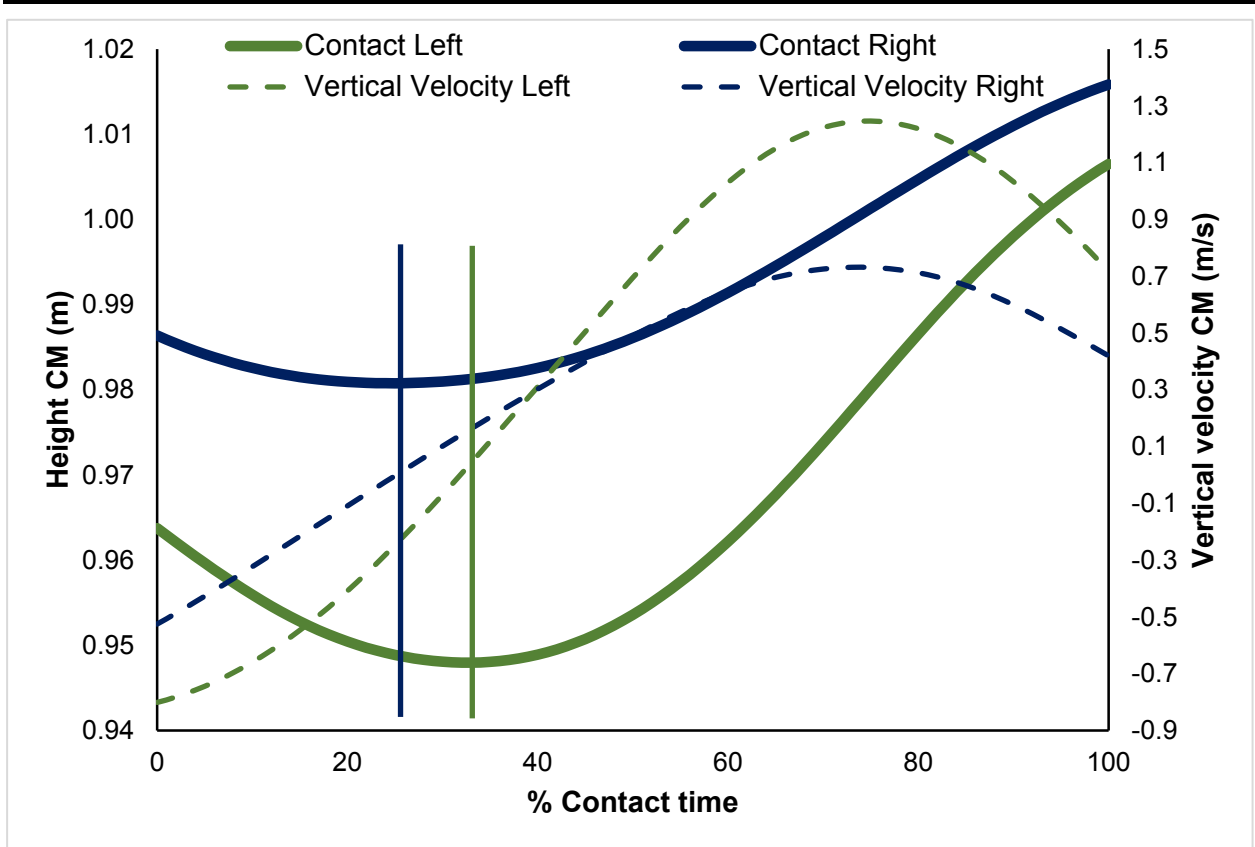


Figure 14.6. CM height and vertical CM velocity during left and right contacts for sixth placed Jimmy Vicaut.

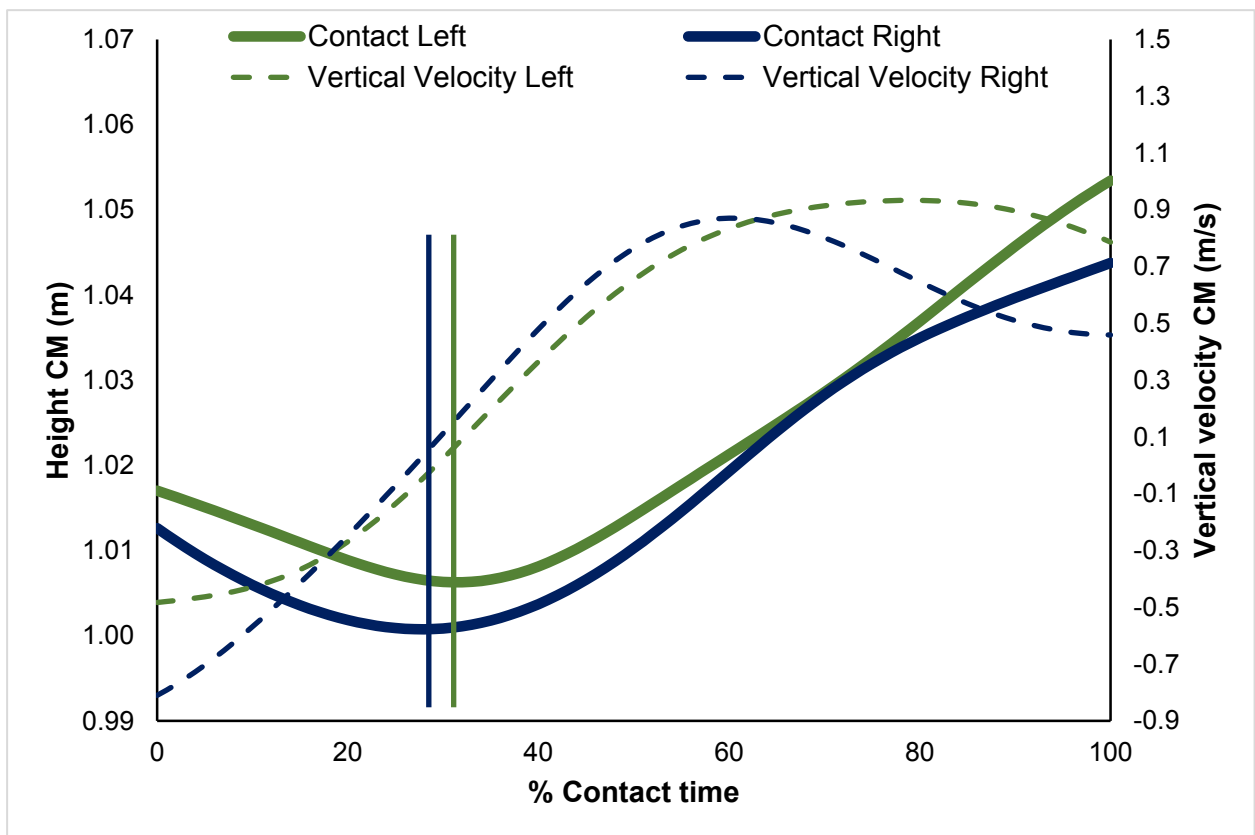


Figure 14.7. CM height and vertical CM velocity during left and right contacts for seventh placed Reece Prescod.

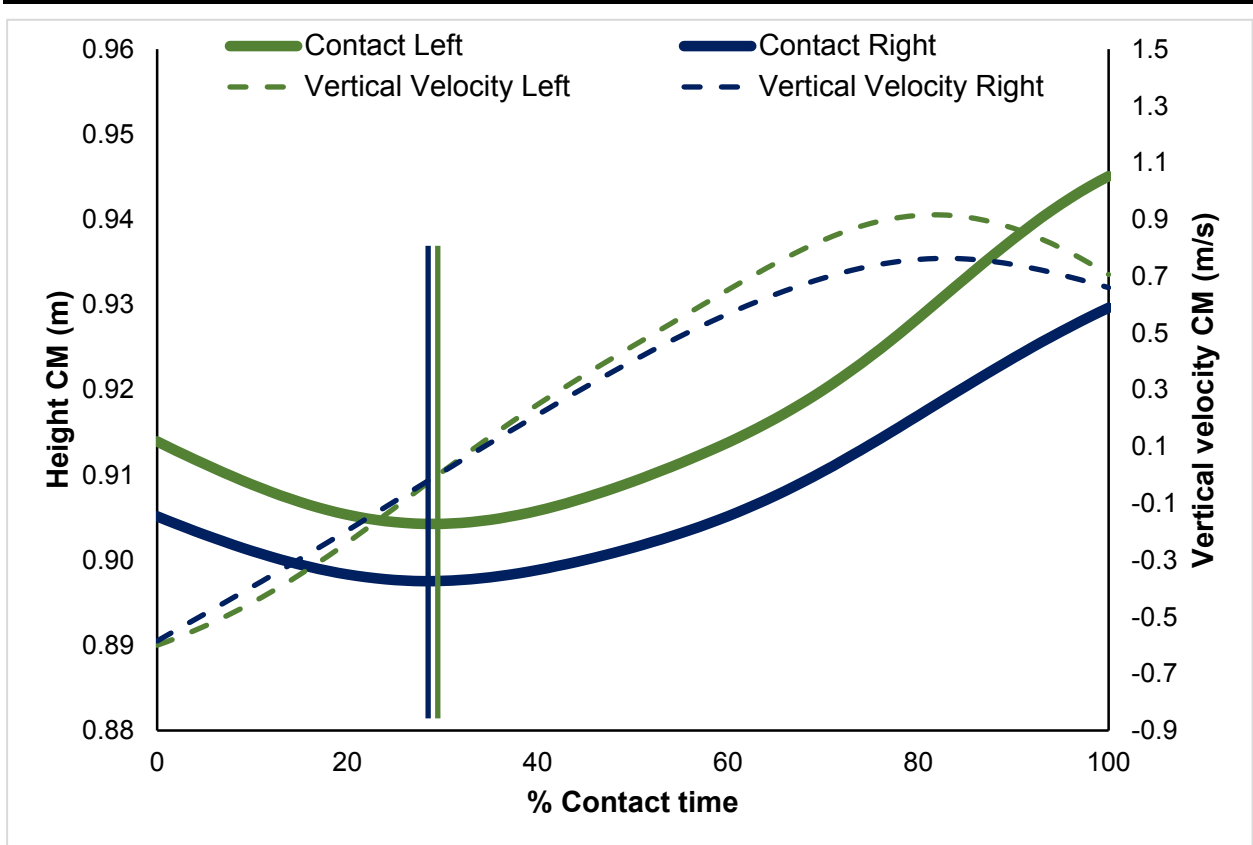


Figure 14.8. CM height and vertical CM velocity during left and right contacts for eighth placed Bingtian Su.

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 CM 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.

<b>Foot horizontal velocity pre-TD (m/s)</b>			
	<b>Left</b>	<b>Right</b>	<b>Mean</b>
<b>GATLIN</b>	3.58	3.71	3.65
<b>COLEMAN</b>	3.81	5.12	4.47
<b>BOLT</b>	3.27	1.91	2.59
<b>BLAKE</b>	2.64	2.94	2.79
<b>SIMBINE</b>	2.84	3.24	3.04
<b>VICAUT</b>	3.17	3.10	3.14
<b>PRESCOD</b>	2.92	3.93	3.43
<b>SU</b>	3.60	3.00	3.30
<b>Foot horizontal velocity TD (m/s)</b>			
	<b>Left</b>	<b>Right</b>	<b>Mean</b>
<b>GATLIN</b>	2.65	2.65	2.65
<b>COLEMAN</b>	2.72	3.75	3.24
<b>BOLT</b>	2.21	1.16	1.69
<b>BLAKE</b>	1.80	2.09	1.95
<b>SIMBINE</b>	2.00	2.42	2.21
<b>VICAUT</b>	2.29	2.19	2.24
<b>PRESCOD</b>	1.97	2.93	2.45
<b>SU</b>	2.81	2.16	2.49

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



Table 8. Vertical velocity of the foot CM 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.

<b>Foot vertical velocity pre-TD (m/s)</b>			
	<b>Left</b>	<b>Right</b>	<b>Mean</b>
<b>GATLIN</b>	-3.88	-3.09	-3.49
<b>COLEMAN</b>	-2.78	-3.11	-2.95
<b>BOLT</b>	-3.37	-2.76	-3.07
<b>BLAKE</b>	-2.81	-2.38	-2.60
<b>SIMBINE</b>	-3.05	-3.46	-3.26
<b>VICAUT</b>	-3.18	-3.50	-3.34
<b>PRESCOD</b>	-2.89	-3.17	-3.03
<b>SU</b>	-3.64	-3.55	-3.60
<b>Foot vertical velocity TD (m/s)</b>			
	<b>Left</b>	<b>Right</b>	<b>Mean</b>
<b>GATLIN</b>	-3.28	-2.44	-2.86
<b>COLEMAN</b>	-2.12	-2.57	-2.35
<b>BOLT</b>	-2.86	-1.87	-2.37
<b>BLAKE</b>	-1.96	-1.57	-1.77
<b>SIMBINE</b>	-2.25	-2.97	-2.61
<b>VICAUT</b>	-2.43	-2.72	-2.58
<b>PRESCOD</b>	-2.15	-2.69	-2.42
<b>SU</b>	-3.04	-2.68	-2.86

*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
<b>GATLIN</b>	16.71	37	37	20.96	67
<b>COLEMAN</b>	17.92	28	39	20.29	66
<b>BOLT</b>	20.83	26	33	21.83	62
<b>BLAKE</b>	19.68	28	32	21.48	62
<b>SIMBINE</b>	17.85	27	31	20.51	53
<b>VICAUT</b>	17.25	28	28	20.48	57
<b>PRESCOD</b>	17.48	29	33	20.25	57
<b>SU</b>	17.80	28	30	21.78	61

**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.

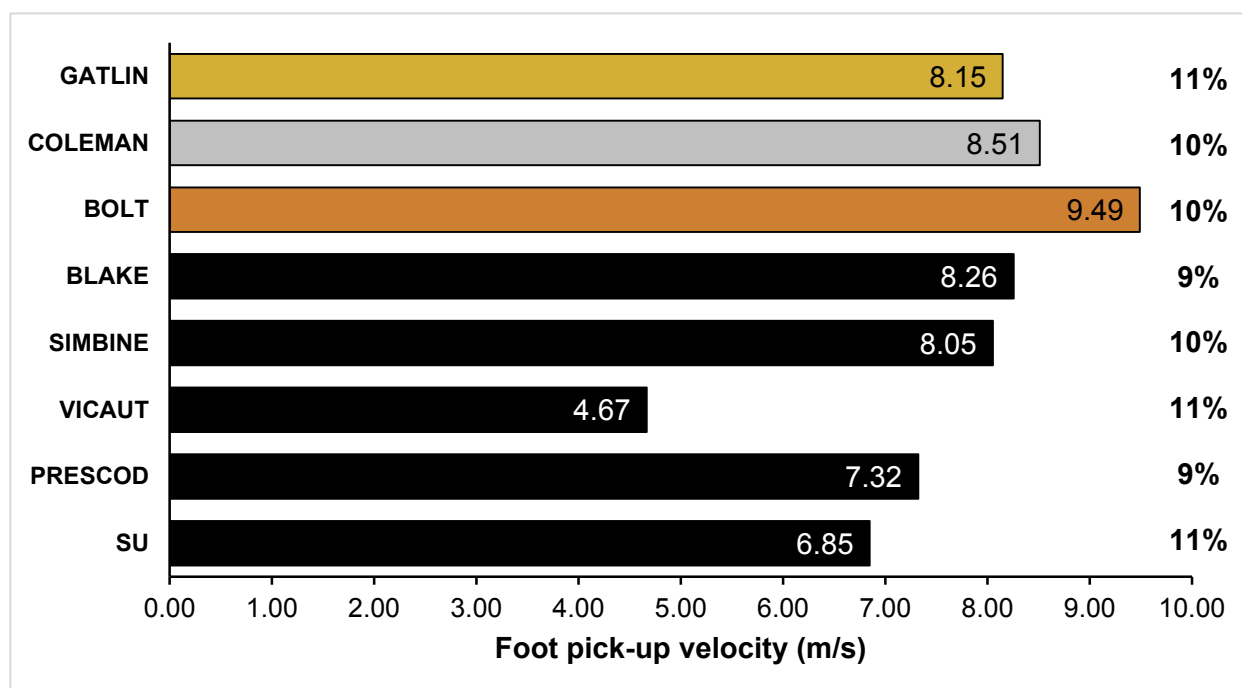


Figure 15. The peak vertical velocity of the foot CM during the swing phase. For all athletes, this peak value occurred shortly after toe-off and has been termed 'foot pick-up velocity'.

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.

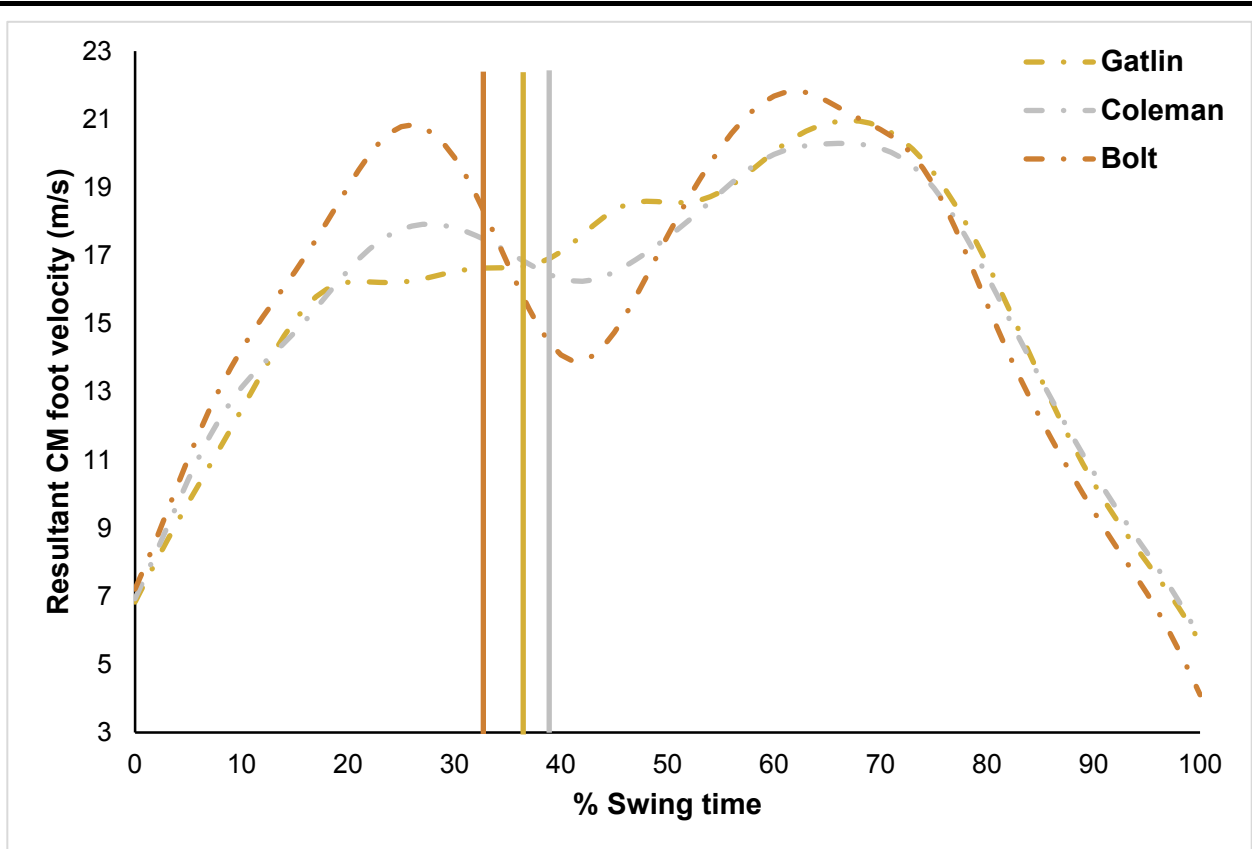


Figure 16.1. Resultant foot CM velocity during the swing phase for the three medallists, displayed as a percentage of swing time.

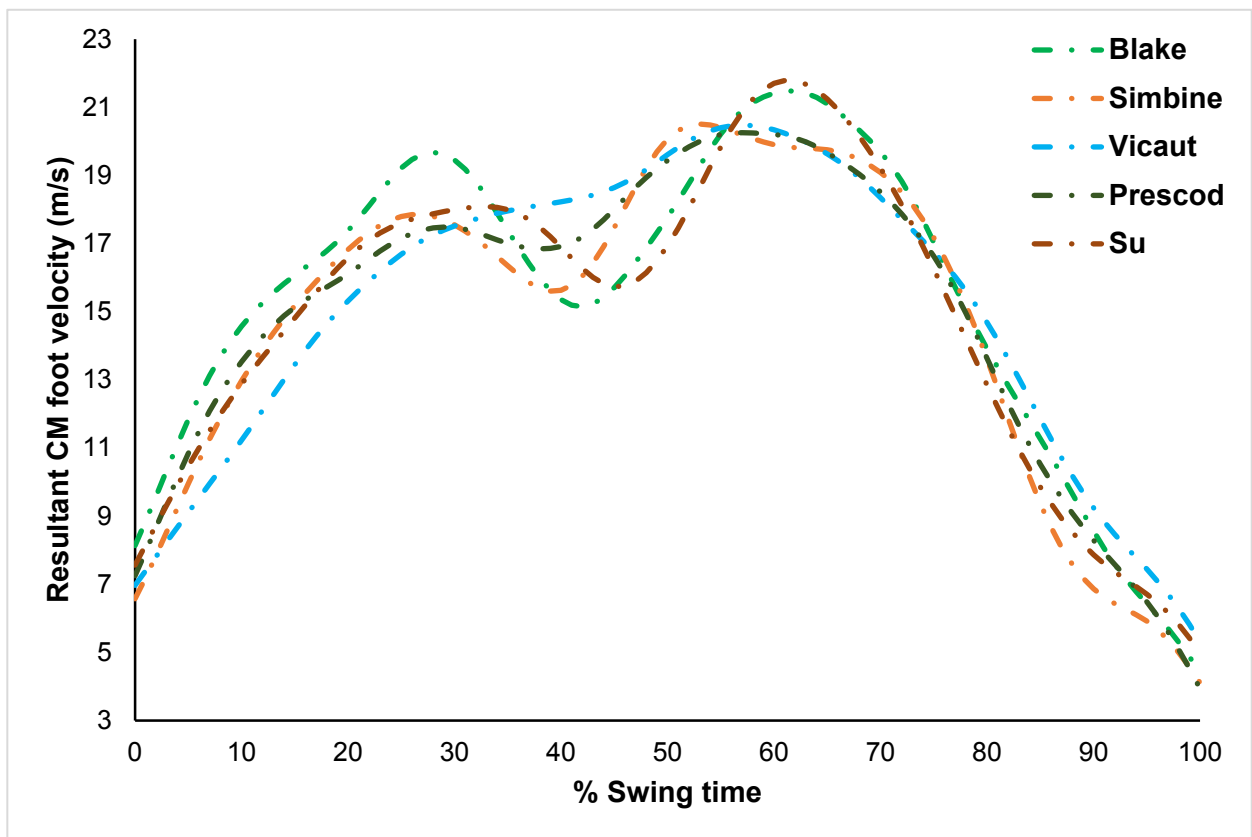


Figure 16.2. Resultant foot CM velocity during the swing phase for the remaining finalists, displayed as a percentage of swing time.

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.

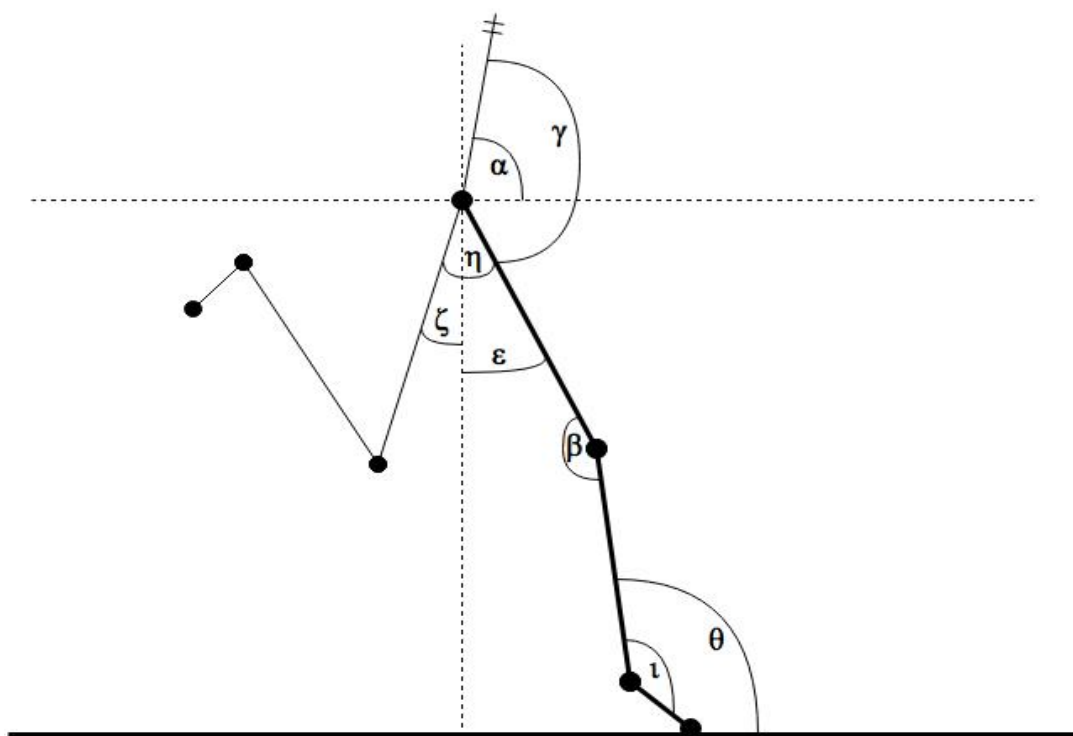


Figure 17. Body schematic denoting angles measured at touchdown. This does not represent any athlete's posture but is merely for illustration purposes.

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

	GATLIN		COLEMAN		BOLT	
	Left (°)	Right (°)	Left (°)	Right (°)	Left (°)	Right (°)
$\alpha$	73.3	73.4	76.5	74.2	76.8	72.7
$\beta$	152.7	148.9	152.0	143.4	161.5	157.1
$\gamma$	126.7	132.5	144.1	134.7	140.6	142.7
$\epsilon$	36.9	33.7	27.4	36.3	28.8	22.2
$\zeta$	12.1	6.0	1.5	7.4	7.2	26.8
$\eta$	-24.8	-27.7	-25.9	-28.9	-21.6	4.6
$\theta$	103.0	98.1	105.7	95.4	103.7	95.4
$\iota$	120.2	111.5	122.3	115.1	122.5	116.2

**Note:** For angles  $\epsilon$  and  $\zeta$ , a positive value indicates that the thigh segment was in front of the vertical axis. For angle  $\eta$ , 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.

	BLAKE		SIMBINE		VICAUT	
	Left (°)	Right (°)	Left (°)	Right (°)	Left (°)	Right (°)
$\alpha$	69.6	73.3	71.9	76.9	82.2	78.6
$\beta$	162.1	160.0	158.0	156.3	155.2	151.5
$\gamma$	136.5	139.9	137.2	143.2	143.5	139.4
$\varepsilon$	23.2	24.2	24.5	26.0	28.9	30.1
$\zeta$	23.7	19.4	25.3	20.7	24.5	25.3
$\eta$	0.5	-4.8	0.8	-5.3	-4.4	-4.8
$\theta$	100.2	98.5	93.4	92.3	96.2	92.4
$\iota$	117.4	120.8	118.4	112.8	111.4	108.7

	PRESCOD		SU	
	Left (°)	Right (°)	Left (°)	Right (°)
$\alpha$	71.6	77.9	79.2	79.3
$\beta$	168.5	165.7	167.3	144.2
$\gamma$	142.5	148.9	149.3	139.1
$\varepsilon$	18.3	22.7	24.2	30.9
$\zeta$	26.2	11.5	18.6	23.4
$\eta$	7.9	-11.2	-5.6	-7.5
$\theta$	97.8	98.5	104.2	97.6
$\iota$	117.8	114.1	123.9	108.6

**Note:** For angles  $\varepsilon$  and  $\zeta$ , a positive value indicates that the thigh segment was in front of the vertical axis. For angle  $\eta$ , 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.

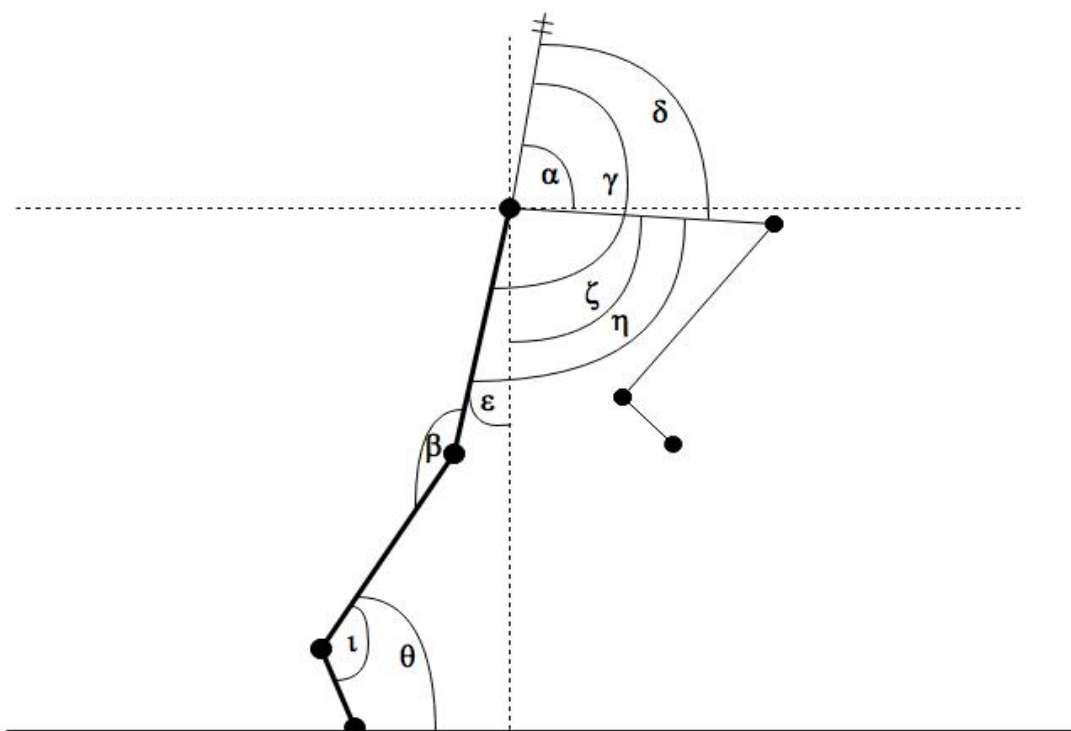


Figure 18. Body schematic denoting joint angles measured at toe-off. This does not represent any athlete's posture but is merely for illustration purposes.

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

	GATLIN		COLEMAN		BOLT	
	Left (°)	Right (°)	Left (°)	Right (°)	Left (°)	Right (°)
$\alpha$	77.9	81.2	83.9	83.3	81.2	79.6
$\beta$	160.5	155.0	159.5	155.2	151.9	159.6
$\gamma$	193.7	191.8	205.2	196.7	194.1	202.7
$\delta$	105.7	110.9	116.1	120.5	101.1	106.3
$\epsilon$	-28.7	-26.2	-28.9	-26.9	-23.5	-28.2
$\zeta$	66.4	66.7	56.4	58.6	70.6	68.4
$\eta$	95.1	92.9	85.3	85.5	94.1	96.6
$\theta$	41.5	38.6	40.6	38.3	38.4	41.4
$\iota$	146.5	132.0	131.3	140.7	137.3	137.7

**Note:** For angles  $\epsilon$  and  $\zeta$ , a positive value indicates that the thigh segment was in front of the vertical axis. For angle  $\eta$ , 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.

	BLAKE		SIMBINE		VICAUT	
	Left (°)	Right (°)	Left (°)	Right (°)	Left (°)	Right (°)
$\alpha$	78.9	74.8	82.6	81.9	85.3	84.2
$\beta$	157.0	157.6	151.9	149.3	153.2	138.2
$\gamma$	199.0	196.7	197.7	193.0	198.7	193.5
$\delta$	96.6	90.6	106.6	113.1	101.1	108.4
$\epsilon$	-31.0	-27.0	-25.9	-22.2	-25.9	-13.5
$\zeta$	74.3	77.1	54.7	65.2	75.1	70.6
$\eta$	105.3	104.1	80.6	87.4	101.0	84.1
$\theta$	36.2	41.2	36.3	37.2	37.7	34.6
$\iota$	146.6	141.6	142.4	136.0	149.7	132.3

	PRESCOD		SU	
	Left (°)	Right (°)	Left (°)	Right (°)
$\alpha$	74.5	76.7	81.9	83.5
$\beta$	156.0	152.2	153.1	154.7
$\gamma$	193.9	190.8	193.3	201.0
$\delta$	96.1	103.5	98.5	106.3
$\epsilon$	-26.0	-21.2	-24.3	-27.2
$\zeta$	68.5	67.6	76.6	71.1
$\eta$	94.5	88.8	100.9	98.3
$\theta$	40.1	41.0	39.4	38.8
$\iota$	133.1	135.2	140.9	137.9

**Note:** For angles  $\epsilon$  and  $\zeta$ , a positive value indicates that the thigh segment was in front of the vertical axis. For angle  $\eta$ , 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 ( $\beta$ ) and ankle ( $\iota$ ) 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 (°)		$\Delta$ knee angle (°)	
	Left	Right	Left	Right
<b>GATLIN</b>	136.7	147.5	16.0	1.4
<b>COLEMAN</b>	146.3	131.9	5.7	11.5
<b>BOLT</b>	140.5	138.7	21.0	18.4
<b>BLAKE</b>	144.1	139.9	18.0	20.1
<b>SIMBINE</b>	138.3	141.1	19.7	15.2
<b>VICAUT</b>	130.4	125.9	24.8	25.6
<b>PRESCOD</b>	146.0	146.0	22.5	19.7
<b>SU</b>	149.8	129.8	17.5	14.4

*Note: Knee angles shown here are represented by angle  $\beta$ ' 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 (°)		$\Delta$ ankle angle (°)	
	Left	Right	Left	Right
<b>GATLIN</b>	86.4	88.8	33.8	22.7
<b>COLEMAN</b>	95.4	80.4	26.9	34.7
<b>BOLT</b>	85.5	87.0	37.0	29.2
<b>BLAKE</b>	88.1	95.6	29.3	25.2
<b>SIMBINE</b>	89.6	85.4	28.8	27.4
<b>VICAUT</b>	82.6	77.3	28.8	31.4
<b>PRESCOD</b>	83.0	85.6	34.8	28.5
<b>SU</b>	87.2	78.2	36.7	30.4

*Note: Ankle angles shown here are represented by angle  $\tau$ ' 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*”).



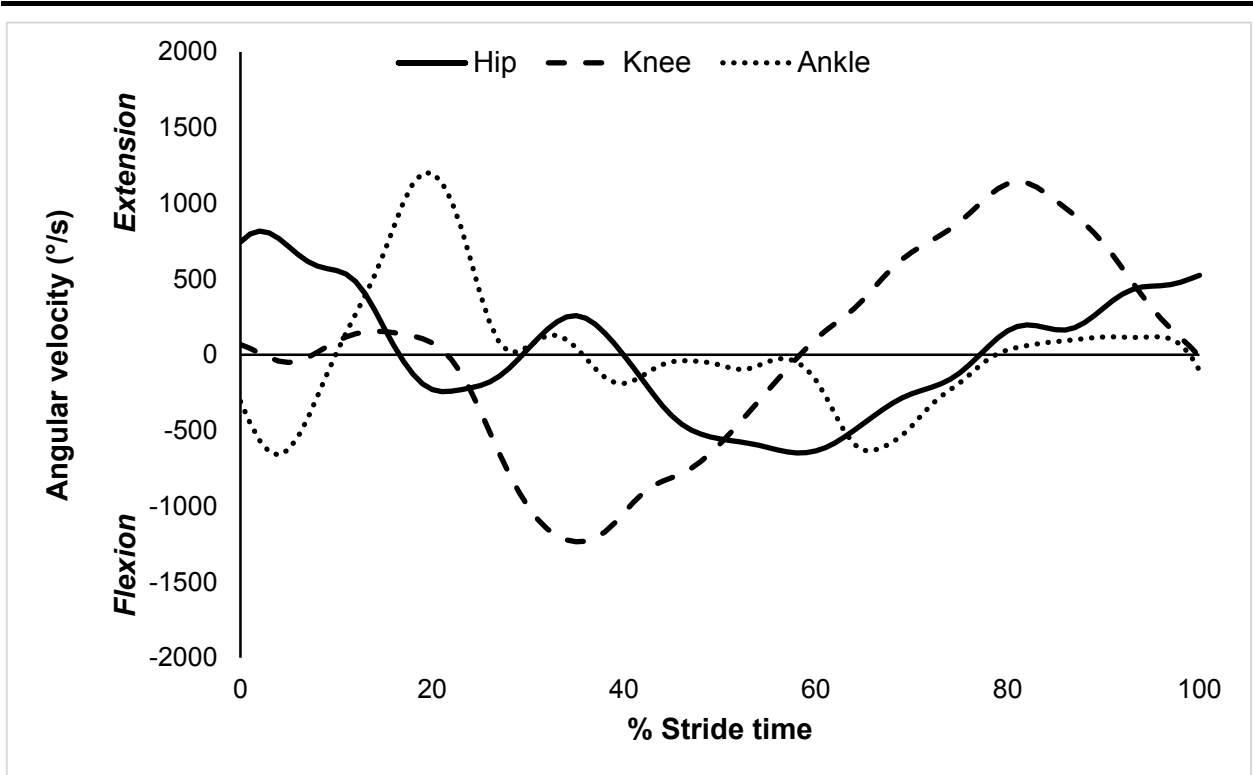


Figure 19.1. Hip, knee and ankle angular velocity over one stride for gold medallist Justin Gatlin.

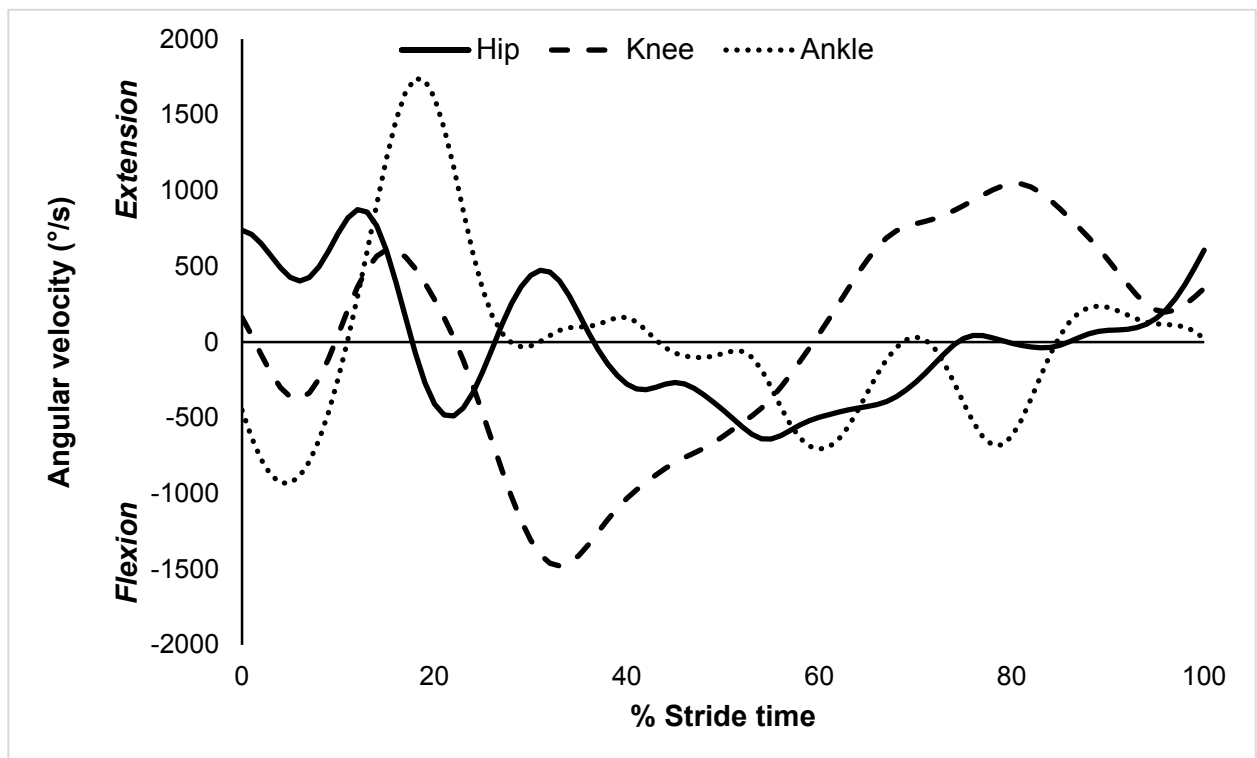


Figure 19.2. Hip, knee and ankle angular velocity over one stride for silver medallist Christian Coleman.

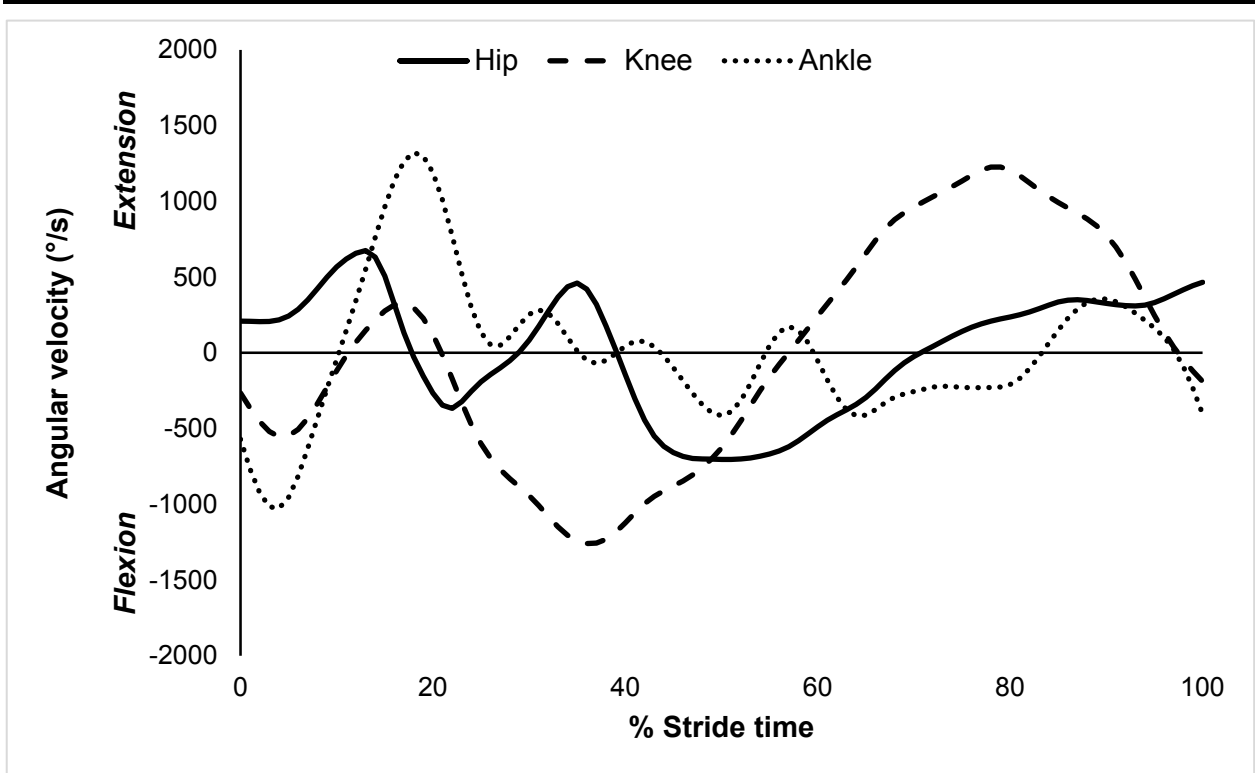


Figure 19.3. Hip, knee and ankle angular velocities over one stride for bronze medallist Usain Bolt.

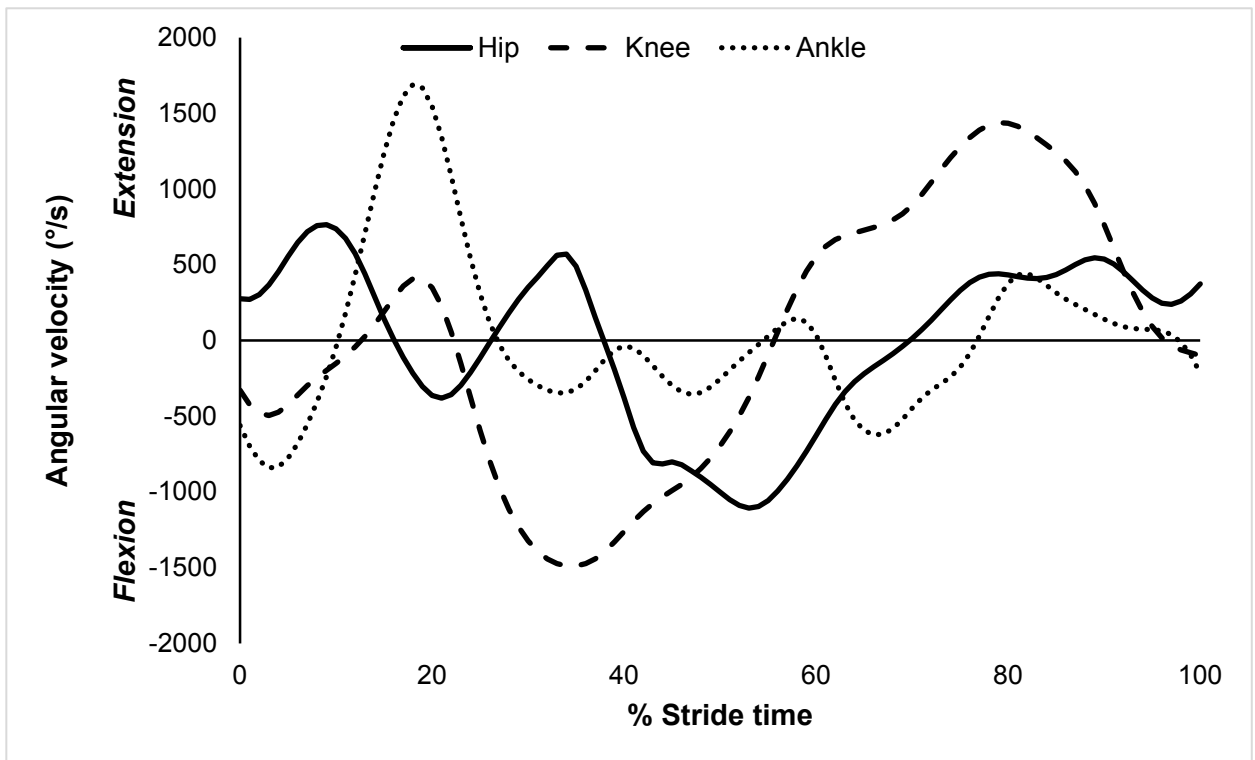


Figure 19.4. Hip, knee and ankle angular velocities over one stride for fourth placed Yohan Blake.

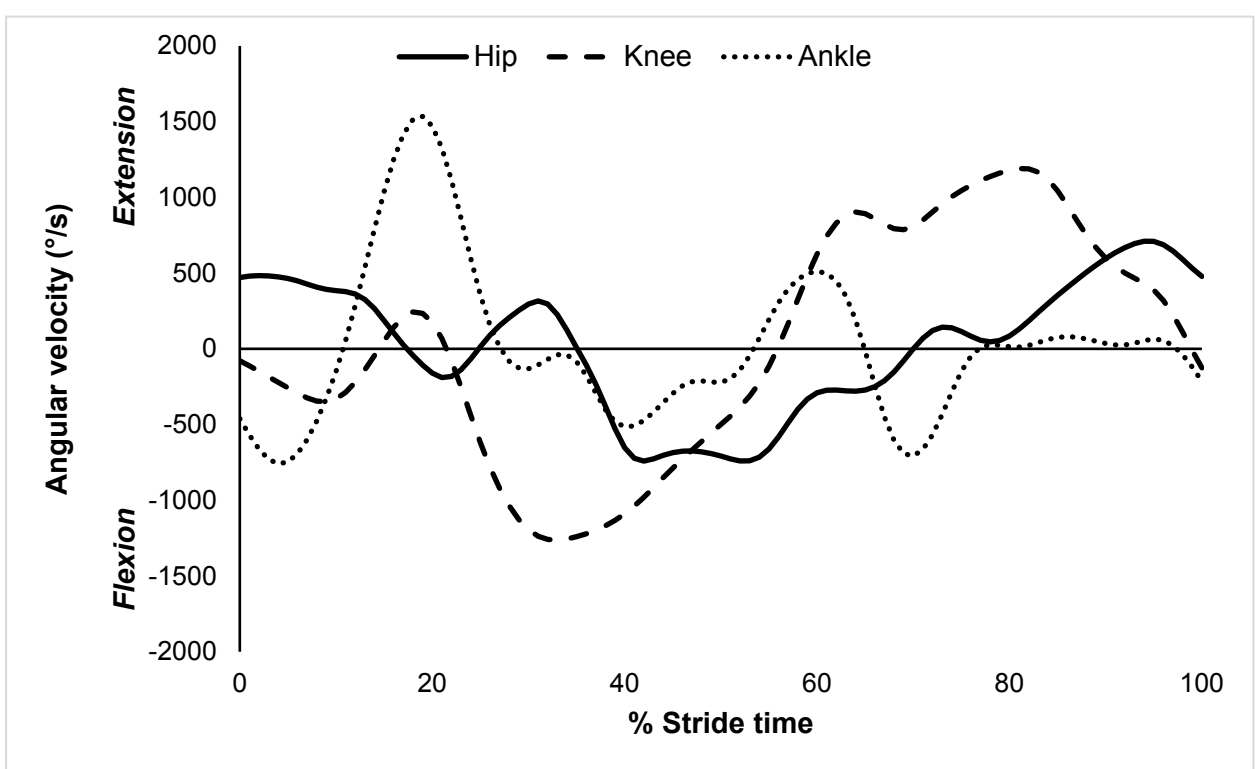


Figure 19.5. Hip, knee and ankle angular velocities over one stride for fifth placed Akani Simbine.

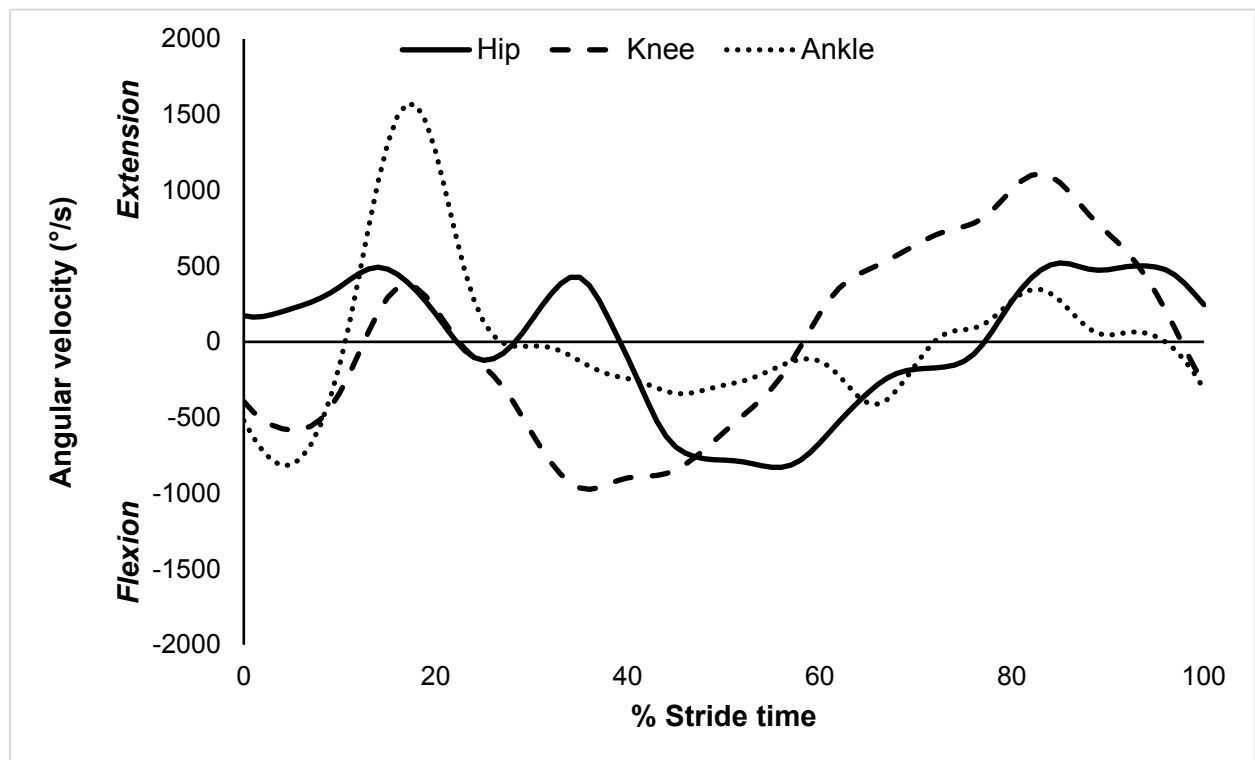


Figure 19.6. Hip, knee and ankle angular velocities over one stride for sixth placed Jimmy Vicaut.

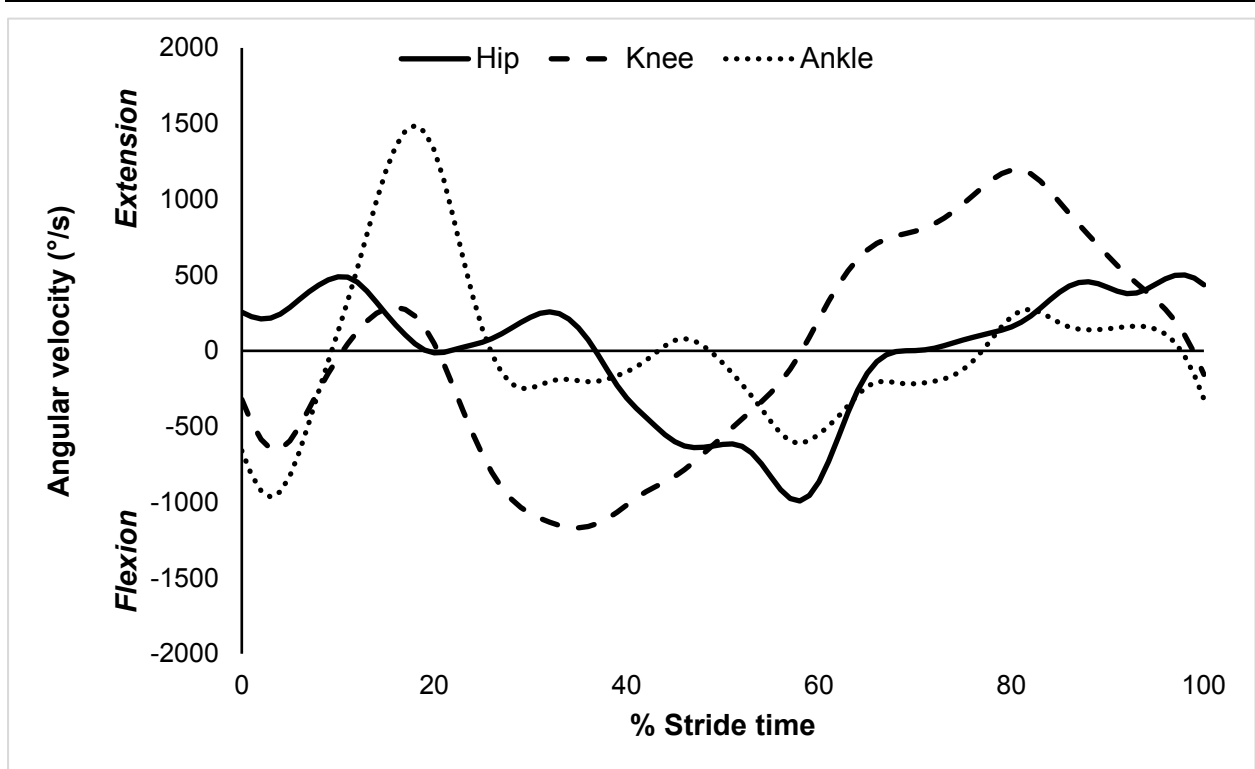


Figure 19.7. Hip, knee and ankle angular velocities over one stride for seventh placed Reece Prescod.

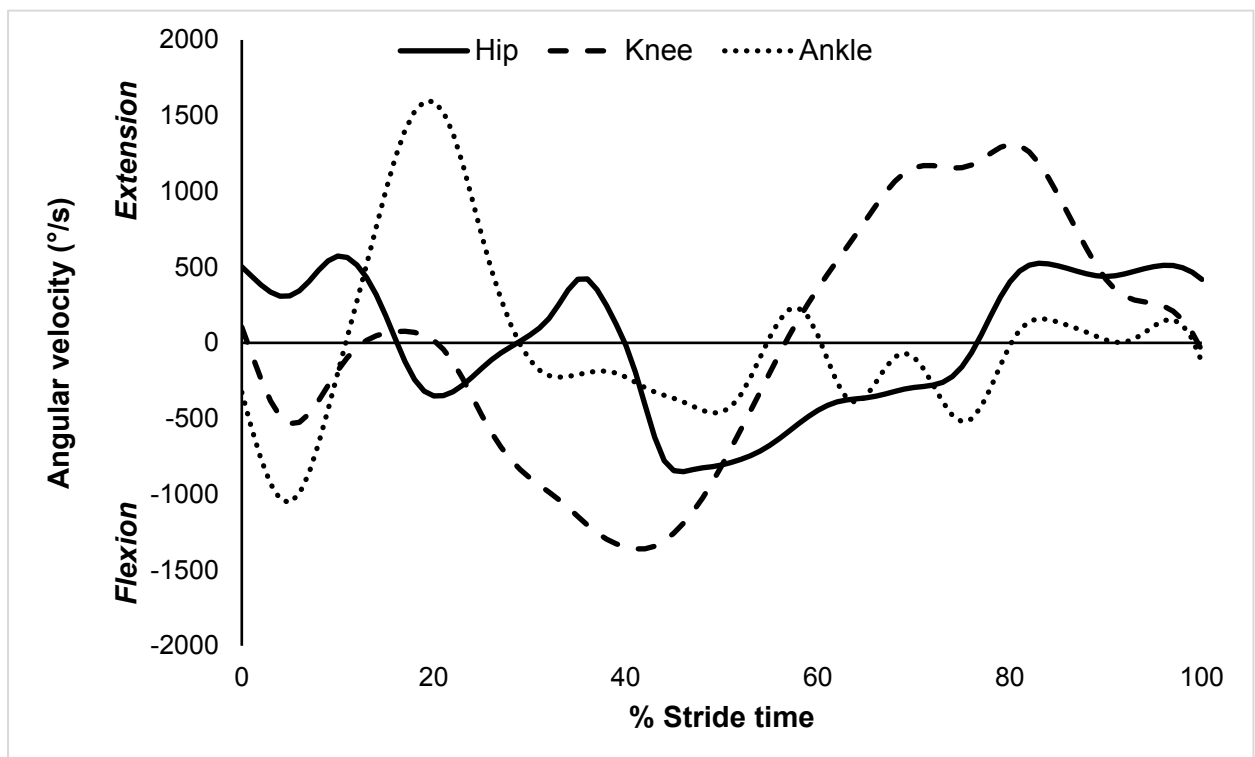


Figure 19.8. Hip, knee and ankle angular velocities over one stride for eighth placed Bingtian Su.

## Final stage of the race

The following section displays key kinematic characteristics for the three medallists during the final two steps (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)
<b>GATLIN</b>	2.70	4.24	11.44
<b>COLEMAN</b>	2.45	4.55	11.14
<b>BOLT</b>	2.87	3.97	11.39

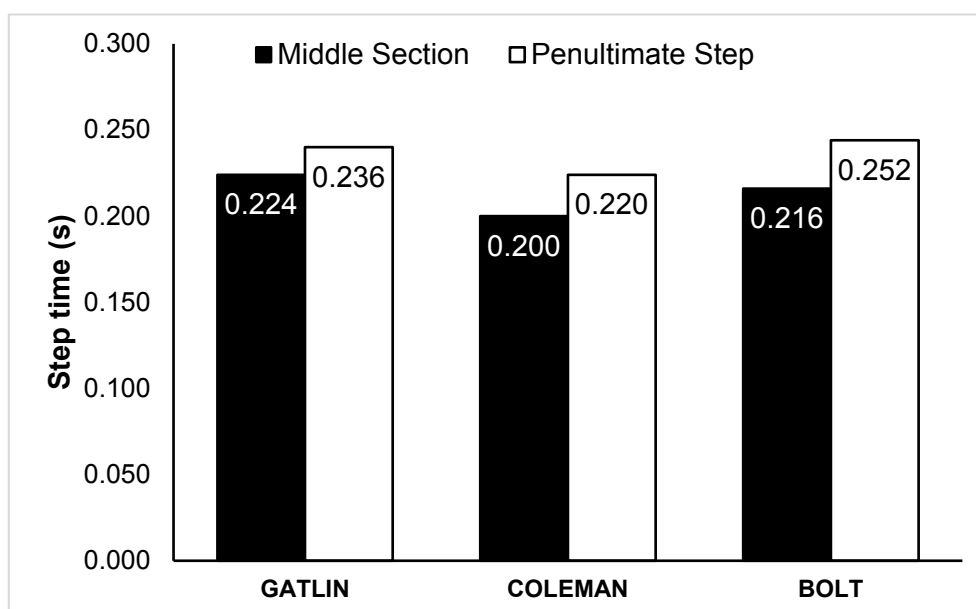


Figure 20. Comparison of step time of the penultimate step and the side-matched analysed step from the middle section of the race. Data shown for each of the medallists.

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 (%)
<b>GATLIN</b>	0.100	0.104	+4.0	0.136	0.140	+2.9
<b>COLEMAN</b>	0.092	0.096	+4.4	0.128	0.164	+28.1
<b>BOLT</b>	0.112	0.104	-7.1	0.140	0.152	+8.6

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

	GATLIN		COLEMAN		BOLT	
	PS (°)	FS (°)	PS (°)	FS (°)	PS (°)	FS (°)
$\alpha$	73.8	66.4	76.0	67.4	72.0	65.1
$\beta$	157.9	167.1	144.2	160.1	149.0	177.0
$\gamma$	141.5	129.0	132.2	141.7	130.0	136.1
$\varepsilon$	29.9	29.0	35.7	23.5	32.8	22.5
$\zeta$	-9.5	-11.2	-12.2	-25.7	10.4	-11.8
$\eta$	-39.4	-40.2	-47.9	-49.2	-22.4	-34.3
$\theta$	102.1	107.9	100.4	107.5	92.6	114.9
$\iota$	116.3	126.1	117.7	126.1	113.8	135.4

**Note:** For angles  $\varepsilon$  and  $\zeta$ , a positive value indicates that the thigh segment was in front of the vertical axis. For angle  $\eta$ , 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 ( $\alpha$ ) 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.

	GATLIN		COLEMAN		BOLT	
	PS (°)	FS (°)	PS (°)	FS (°)	PS (°)	FS (°)
$\alpha$	80.0	66.4	77.2	70.6	80.7	67.7
$\beta$	157.6	167.0	162.7	160.4	169.8	143.7
$\gamma$	199.0	185.0	196.7	198.7	208.2	188.2
$\delta$	119.6	112.9	123.3	109.4	114.7	93.6
$\varepsilon$	-27.2	-30.0	-31.6	-27.2	-34.9	-14.4
$\zeta$	52.1	53.1	51.0	45.1	61.3	63.2
$\eta$	79.3	83.1	82.6	72.3	96.2	77.6
$\theta$	40.8	46.6	42.2	43.8	46.3	39.3
$\iota$	134.0	147.7	135.6	139.2	135.3	146.2

**Note:** For angles  $\varepsilon$  and  $\zeta$ , a positive value indicates that the thigh segment was in front of the vertical axis. For angle  $\eta$ , 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 ( $\alpha$ ) 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.

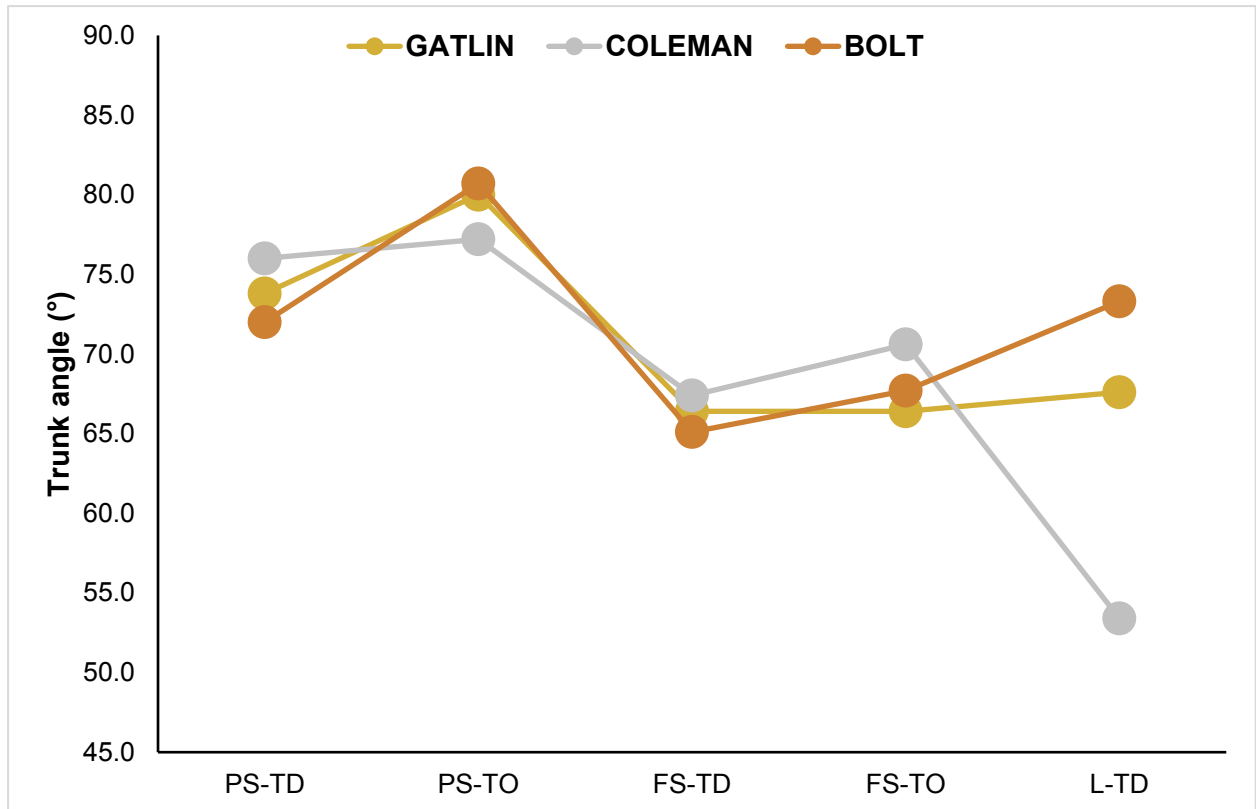


Figure 21. Trunk angle relative to the horizontal (angle  $\alpha$ ) at penultimate step touchdown (PS-TD) and toe-off (PS-TO), final completed step touchdown (FS-TD) and toe-off (FS-TO), and initial ground contact when crossing the line (L-TD). Data displayed for each of the medallists.

## RESULTS – SEMI-FINAL 1

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

### Positional analysis

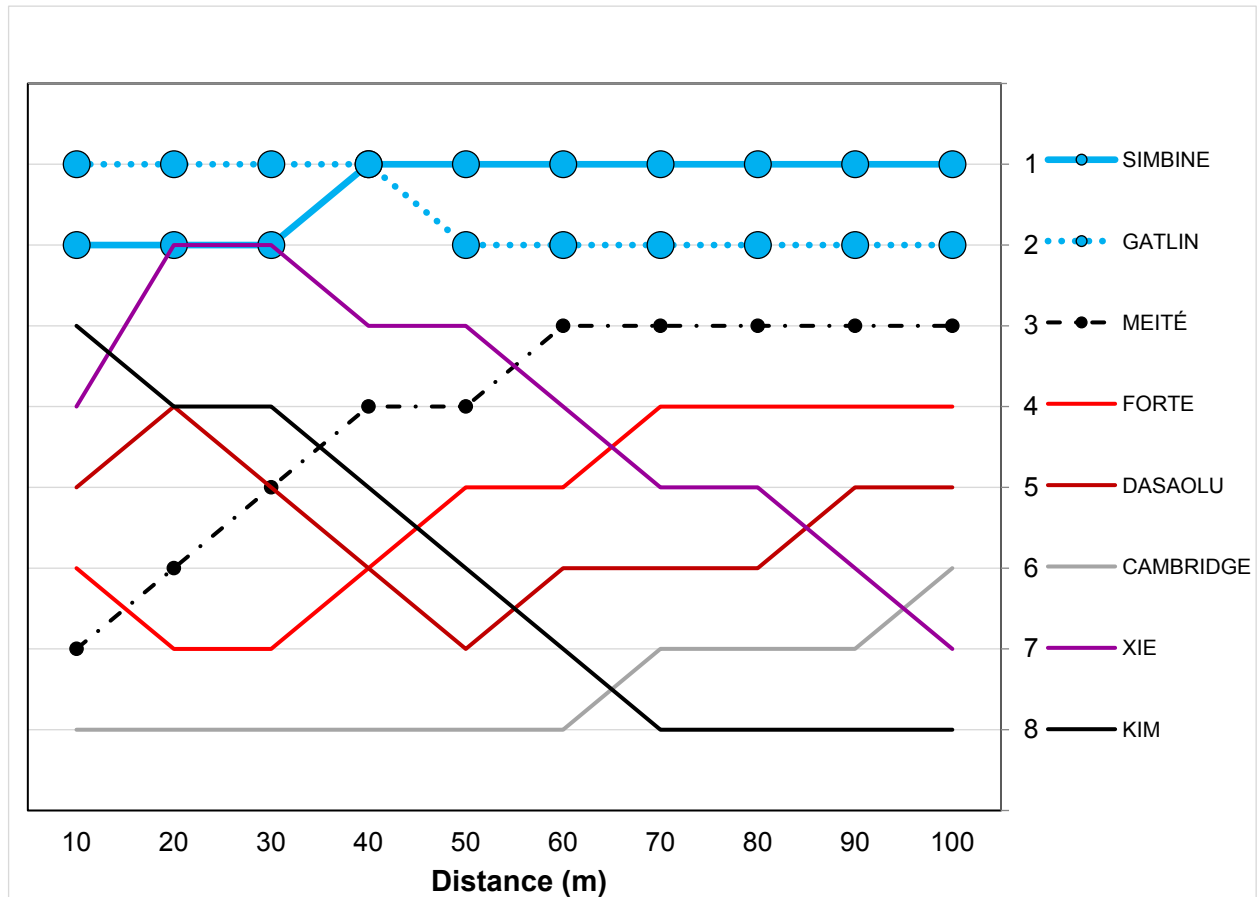


Figure 22. Race position of the athletes from semi-final 1 at each 10-metre split.

**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.

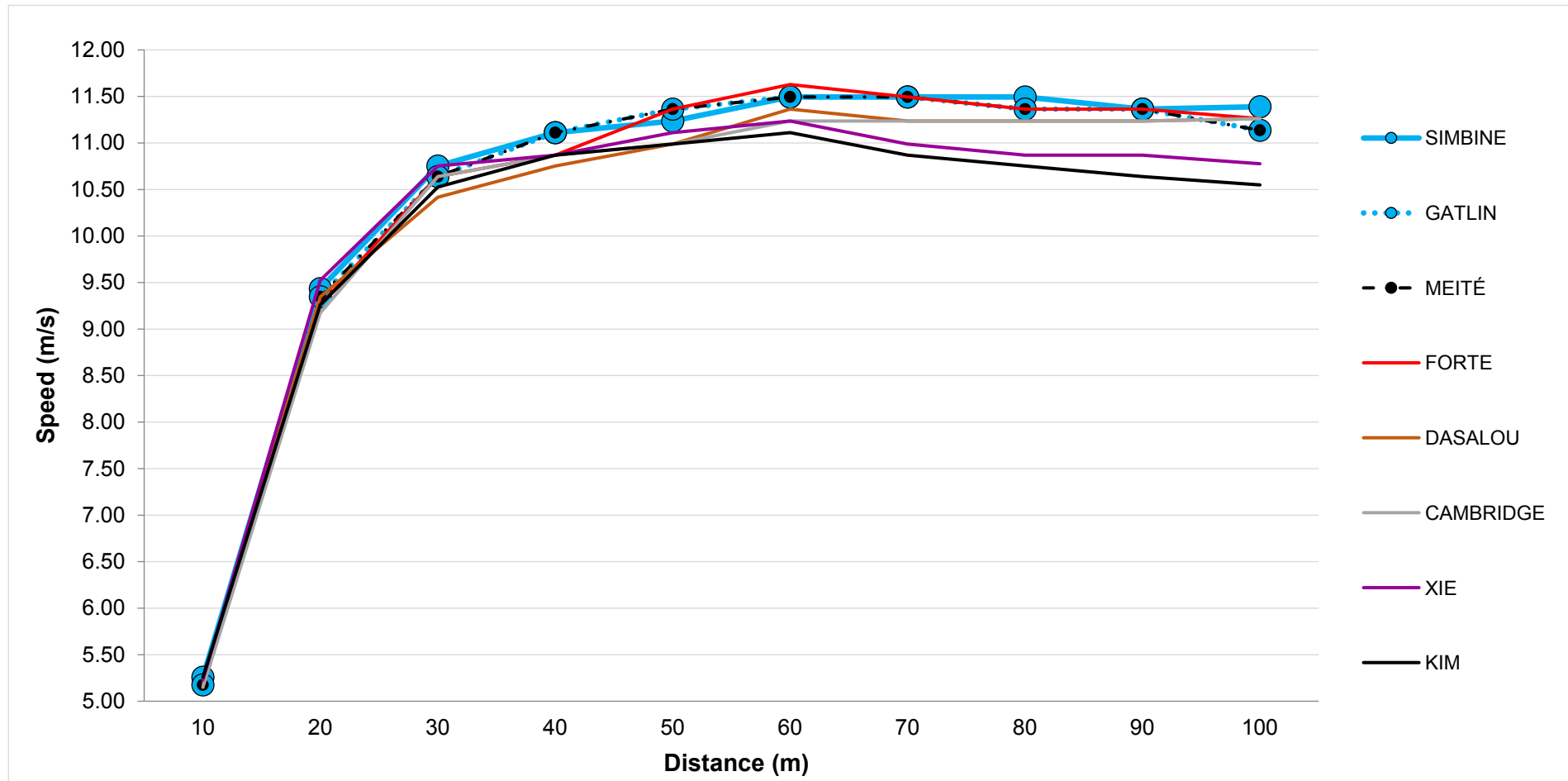


Figure 23. Mean speed over each 10-metre split.

## 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).

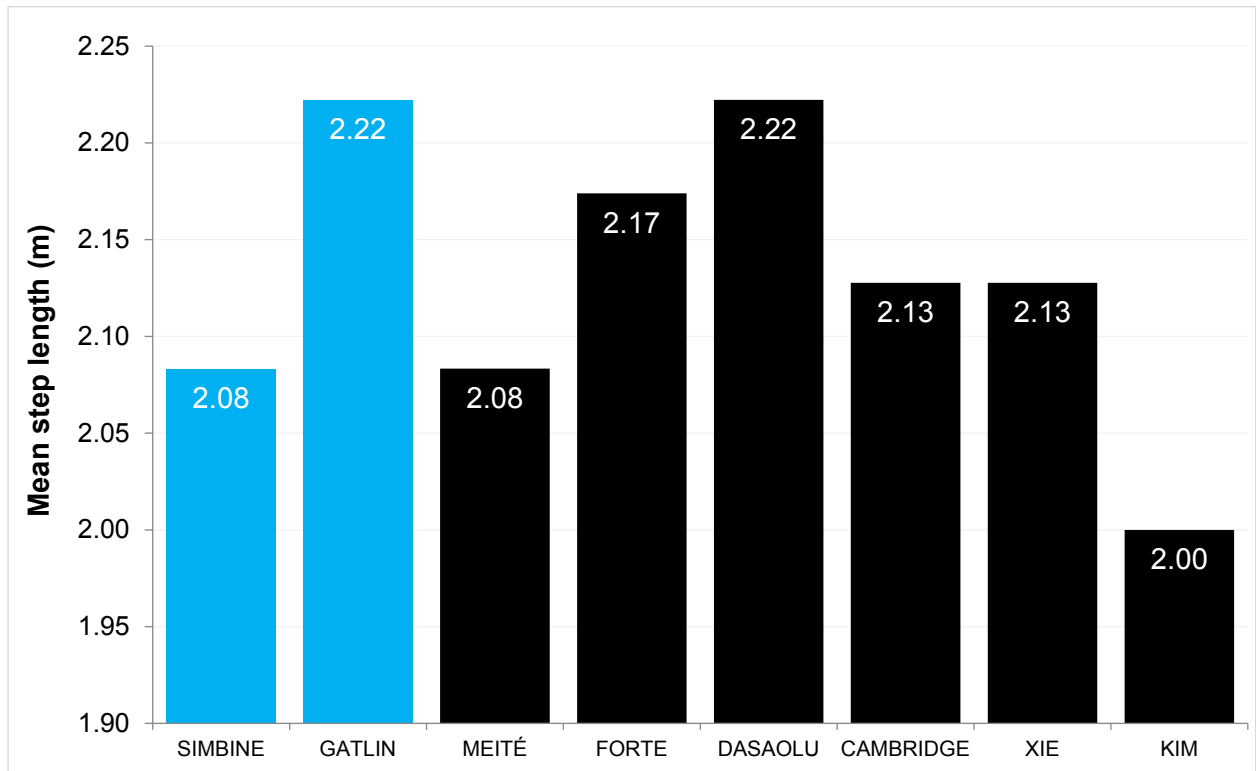


Figure 24. Mean absolute step length for each athlete over 100 metres.

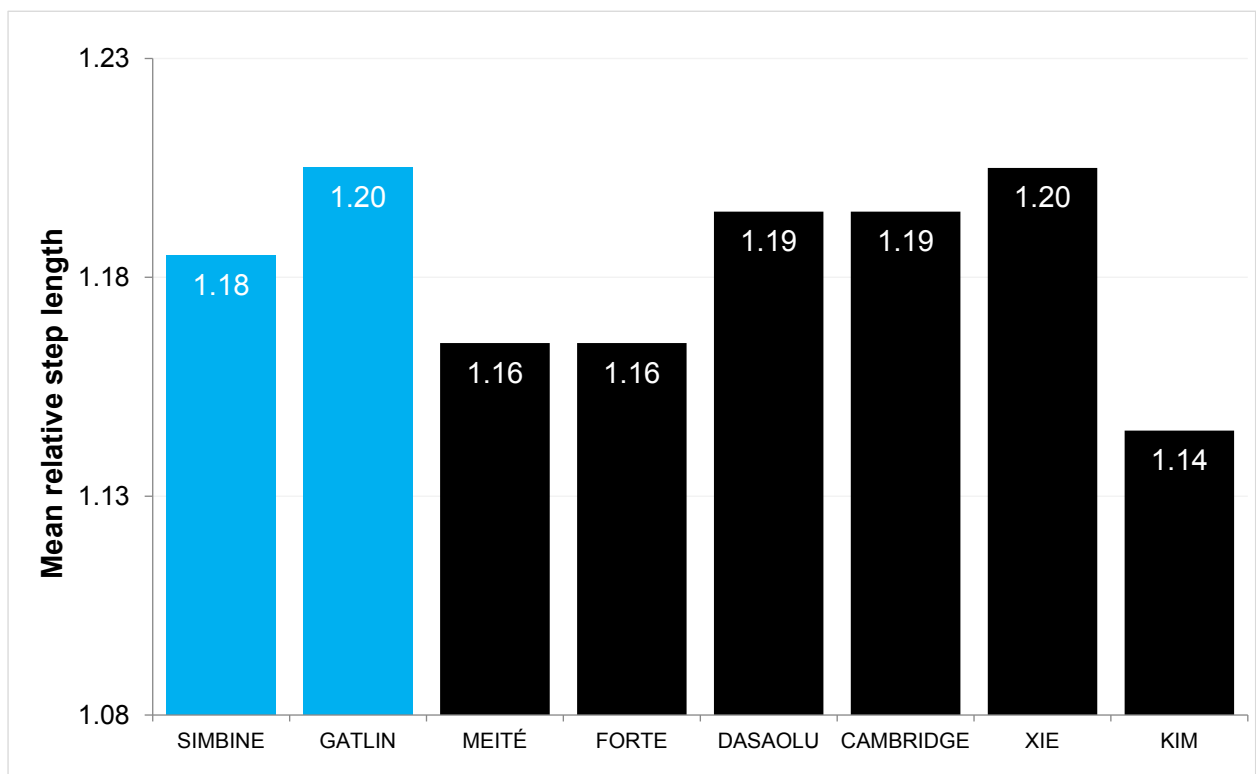


Figure 25. Mean relative step length for each athlete over 100 metres.

## RESULTS – SEMI-FINAL 2

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

### Positional analysis

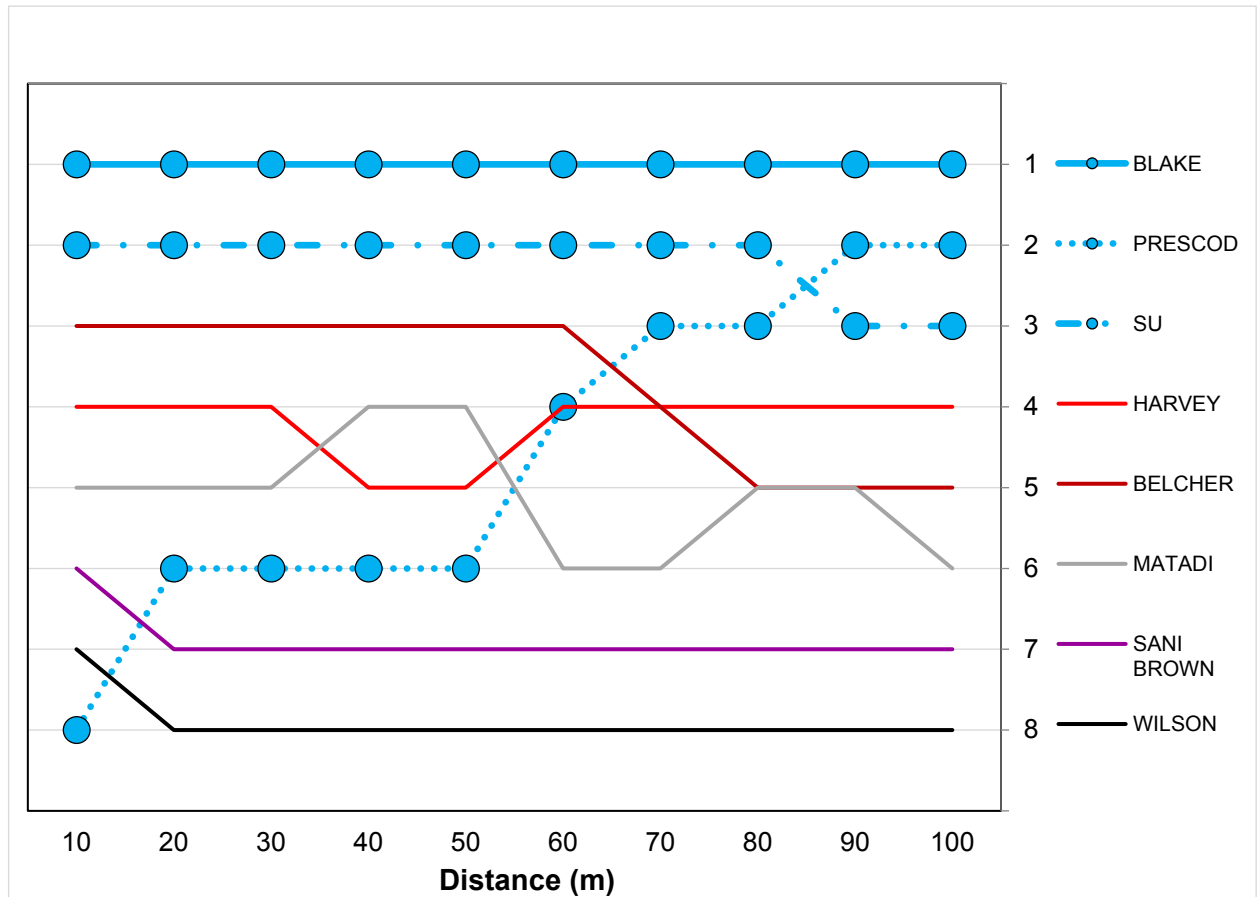


Figure 26. Race position of the athletes from semi-final 2 at each 10-metre split.

**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.

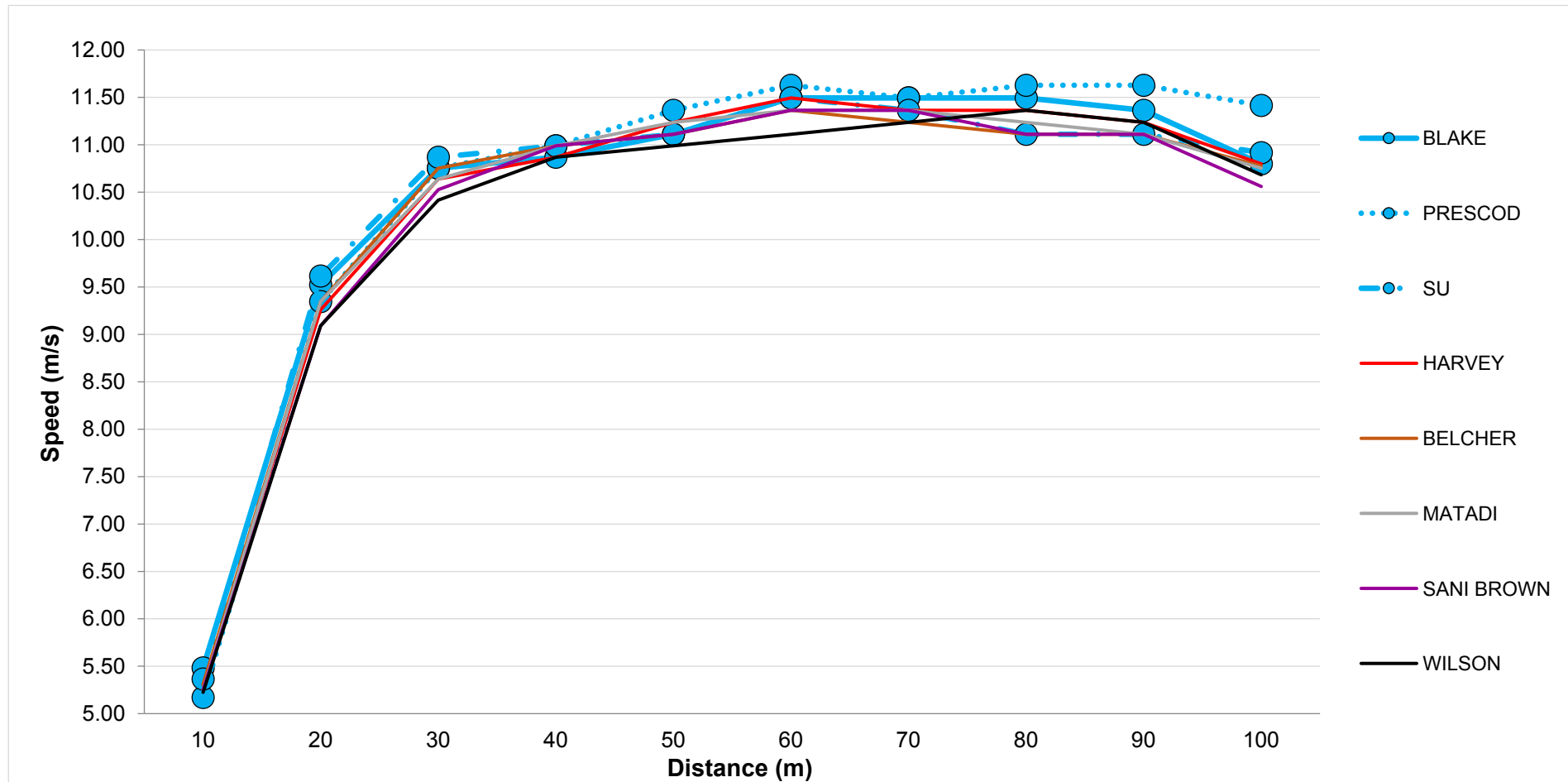


Figure 27. Mean speed over each 10-metre split.

## 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).

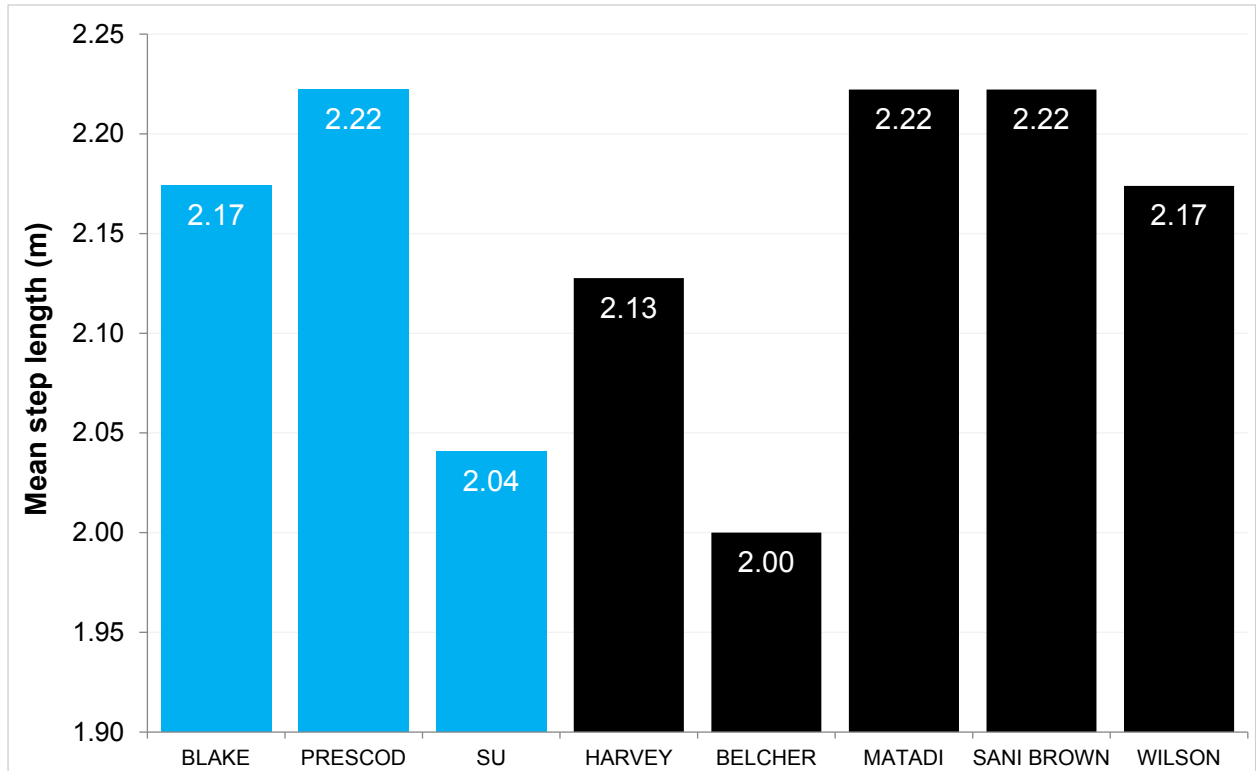


Figure 28. Mean absolute step length for each athlete over 100 metres.

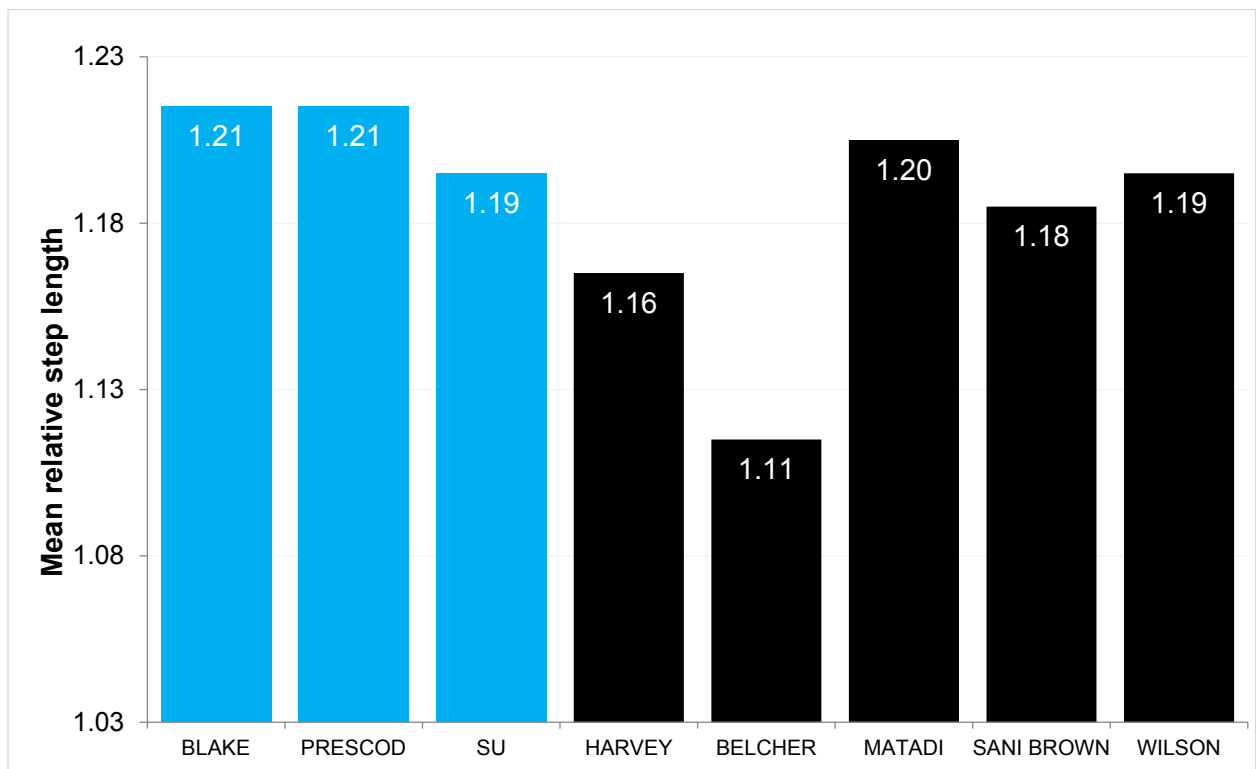


Figure 29. Mean relative step length for each athlete over 100 metres.

## RESULTS – SEMI-FINAL 3

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

### Positional analysis

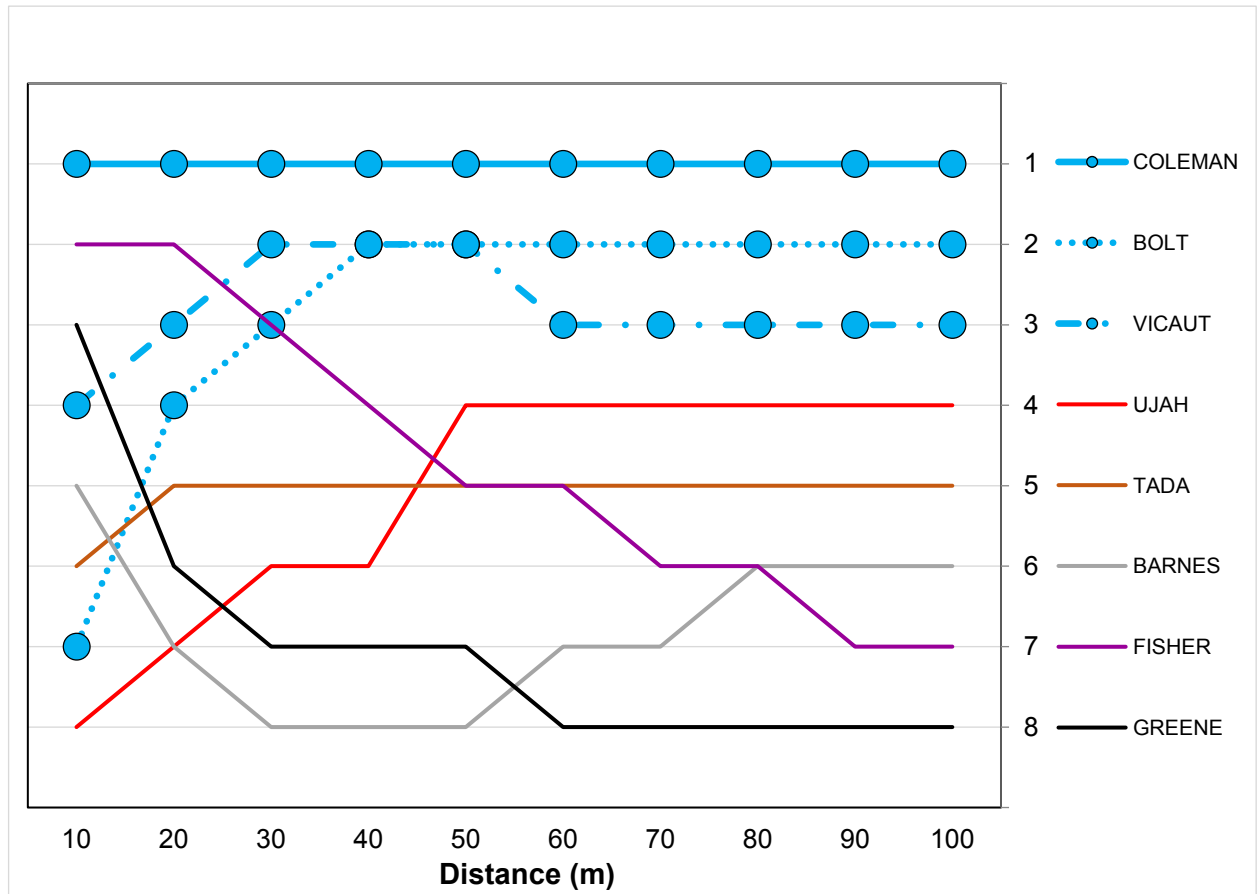


Figure 30. Race position of the athletes from semi-final 3 at each 10-metre split.

**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.

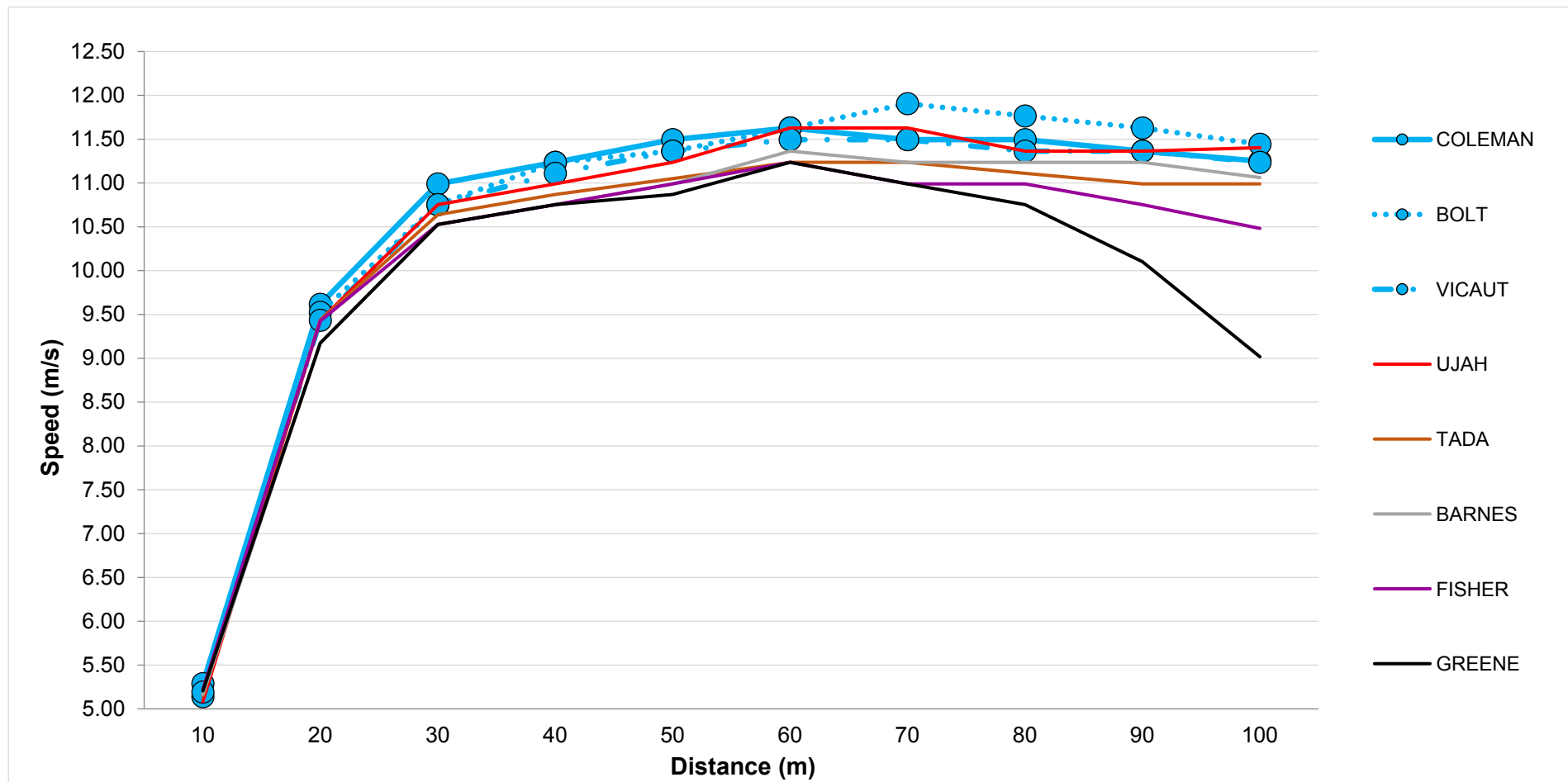


Figure 31. Mean speed over each 10-metre split.

## 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).

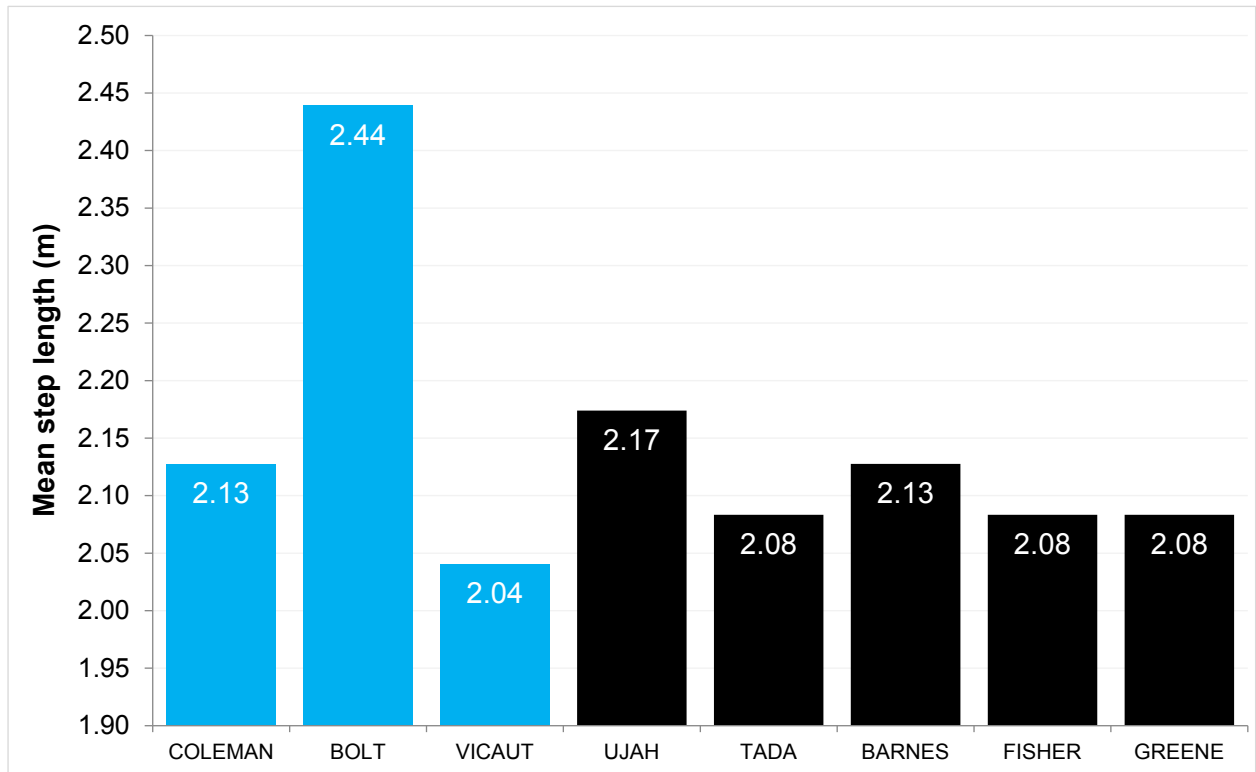


Figure 32. Mean absolute step length for each athlete over 100 metres.

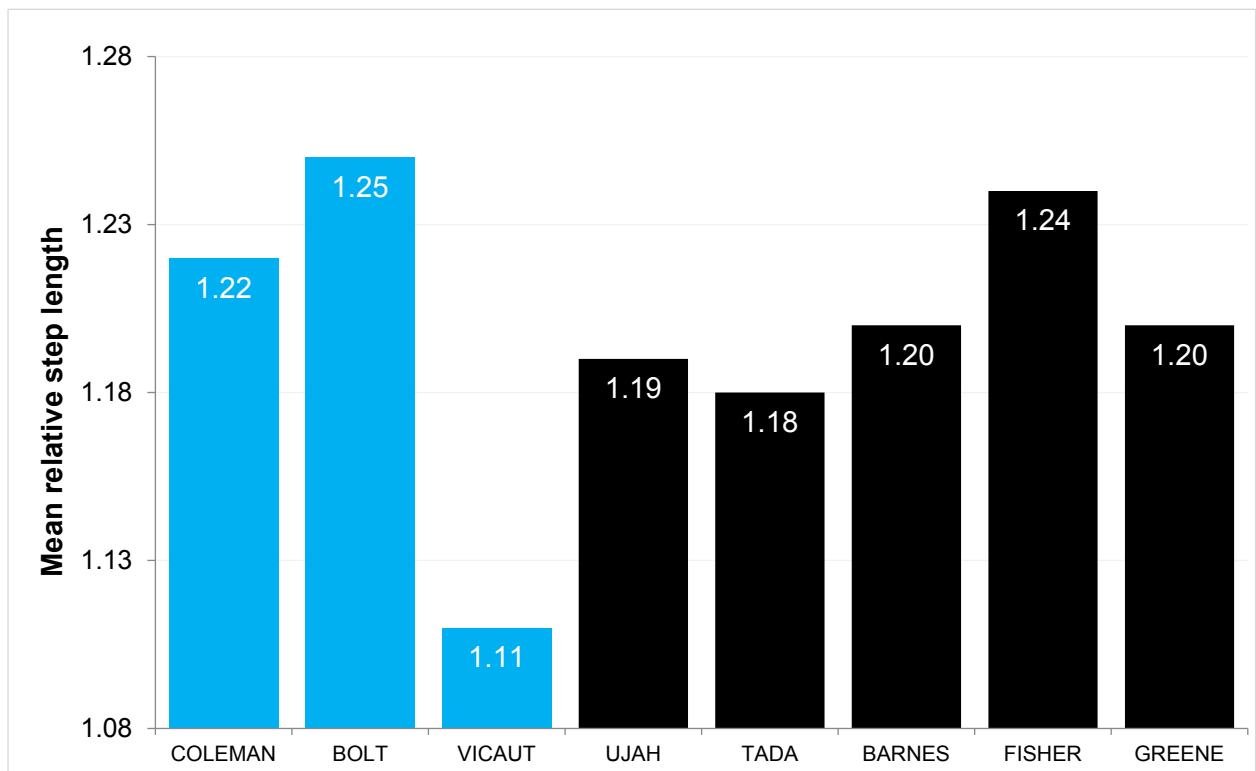


Figure 33. Mean relative step length for each athlete over 100 metres.



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## COACH'S COMMENTARY

### Historical analysis and coaching commentary – Pierre-Jean Vazel

The documentation provided by Leeds Beckett University for the IAAF is exceptional in depth. It gives hints to explain the outcome of the competition in London and delivers a necessary update on the sprinting technique of the world's best athletes. Before entering into technical considerations, it should be stressed that the men's 100 m final was not particularly fast, into a 0.9 m/s wind. Whilst 9 men ran 10.07 s or faster in the heats, only 5 managed it in the semi-finals, and 5 again in the final. In the final, only the two most experienced athletes managed to run their season's bests, Justin Gatlin and Usain Bolt, who together have participated in World Championships (WC) or Olympic games (OG) a total of 19 times. Being able to peak when it counts allowed them to take gold and bronze medals, while the silver went to the youngest sprinter in the field, Christian Coleman, who led the final from the reaction time, passing 30 m in 3.77 s (Table 2.2) – this is the equal fastest time ever recorded (with Michael Green at the 1996 OG and Jon Drummond in Berlin, 2000). However, he eventually lost the race in the final metres (Figure 4). However, all the finalists were far from their personal bests, with a range of 0.12 s (for Akani Simbine) to 0.37 s (for Bolt). The reader will need to keep this in mind when going through the men's report, as the analysis here may not be representative of the best performance of these 8 athletes.

#### Maximum velocity and holding it

A large part of the report focuses on the mid-section of the race, where the highest running velocities are often achieved. Split time analysis during competition in the past 50 years has showed that of all the velocities recorded along the 100 m race, the highest ones, at the mid-way stage, have the strongest relationship with the final result. The best illustration of this is the 1997 IAAF WC, where it was found for 31 runs that the highest velocities, which were recorded at 60 m and 70 m, had the greatest connection with the 100 m time (Kersting, 1999). The 2017 London final was an oddity in that respect. Of all the men's 100 m world or Olympic finals since 1972 where intermediate times were recorded, it is the first where the highest velocity recorded didn't belong to the winner of the race. Simbine may have been the fastest, reaching 11.9 m/s (0.84 s for his best 10 m section), but this didn't compensate for the fact that he was the slowest finalist between 20 m and 40 m and eventually placed 5th overall. It is also interesting to note that 7th placed Prescod had the same velocity peak as winner Gatlin, with 11.6 m/s between 50 and 70 m.

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However, Gatlin displayed the smoothest race distribution and the best speed maintenance, as from the mid-way stage, he virtually held the same speed through the end, keeping his 10 m sections within the same 0.01 s range (0.86-0.87 s). The ability to maintain speed through the line is usually seen as a model and trademark of the best sprinters but this should be reconsidered. While this is true when comparing groups of performers (Türck-Noak, 1996; Kersting, 1999), this feature can be found at any level of performance. For example, one of the first cases recorded was at national level, during a 10.39 s race by Detlef Kübek (GDR, Dresden, 1977), but he ran slightly faster times (10.36 s and 10.37 s) with a normal velocity decline (Hess, 1978). Other notable top sprinters who managed to hold their velocity through the finish line include, Eugen Ray (GDR, 10.30 s, Berlin, 1977), Carl Lewis (USA, 10.02 s, Stuttgart, 1993 WC) or Churandy Martina (AHO, 9.93 s, Beijing, 2008 OG) but they all set their lifetime best races (10.12 s, 9.86 s and 9.91 s, respectively) with a velocity drop. It is noteworthy that none of the 100 m world records or fastest races in history that have been analysed were achieved with perfect speed maintenance. For the current world record of 9.58 s set in Berlin at the 2009 IAAF WC, Usain Bolt held 98% of his top speed during 38 m (Nixdorf, 2009), but this is not more than what he did in slower races of 9.76 s and 9.86 s in Brussels 2011 and 2012 (38 m and 46 m, respectively, adapted from Delecluse, 2012). Nevertheless, regarding Gatlin, this speed maintenance was the main difference in the 2015 IAAF WC final in Beijing, where the American lost his pace against Bolt in the last stage of the race.

### How did Bolt lose?

In London, the 0.03 s difference between Bolt and Gatlin, that cost Bolt the title, could have been saved anywhere in his race, from his relatively poor reaction time of 0.183 s, the slowest he ever did in a championship final, to his top speed (fastest 10 m split of 0.85 s), as he was the fastest of all the semi-finalists the previous day, with a fastest 10 m section of 11.9 m/s (0.84 s). This is still shy of the 12.34 m/s Bolt reached during the world record, the highest speed ever recorded in wind-legal conditions and is equivalent to a 10 m split of 0.81 s (Carl Lewis did 0.80 s, or 12.50 m/s during a +4.3 m/s wind-assisted 100 m in 9.80 s during the quarter-finals of the 1991 IAAF WC; Ae, 1994). The comparison of the kinematic parameters adapted from the work done in Berlin by DLV and JAAF biomechanical teams in Berlin and the ones in the present report, help to understand how Bolt did not run as fast in London. During the 47 m-55.5 m section of the race (i.e., late acceleration phase where the velocity curve almost reaches a plateau), Bolt reached 11.8 m/s in London 2017 and 12.1 m/s in Berlin in 2009. Since running velocity can be calculated from step length and step rate, it is interesting to see which parameter was affected the most: Bolt

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had a slightly longer step length in London than in Berlin (2.70 m vs 2.67 m), however, the main difference was the lower step rate (4.39 Hz vs. 4.55 Hz; average value for consecutive steps).

A lower step rate means that either foot ground contact times or flight times were longer. In Bolt's case, it was both, as in London (2017) the contact times were 0.092 s (right foot) and 0.104 s (left foot), where flight times were 0.124 s and 0.136 s, respectively (see Figure 10). However, in Berlin (2009), the values for both feet were 0.092 s and 0.098 s for contact times, and 0.120 s and 0.132 s for flight times. Longer ground contacts mean that in London, Bolt was not able to produce ground reaction forces as quickly as he could in his prime. Shorter contact times are one of the parameters that remain the most important when comparing sprinters of different levels of performance, from youth or regional class to world medallists. Previous analysis of maximum velocity sections of the 100 m race have reported contact times as short as 0.077 s for Tyson Gay (during a 100 m performance of 9.71 s, Berlin, 2009, Böttcher, 2010) and 0.078 s for Harvey Glance (100 m in 10.09 s, Dresden, 1986, Müller, 1988). Yet, the London 2017 WC showed that even world finalists can display a wide range of contact times, from 0.084 s (Simbine) to 0.104 s (Bolt). It stresses the importance of making the distinction between a general trend drawn from hundreds of subjects, i.e., shorter contacts for faster athletes, and the diversity of the features that can be found in particular athletes. Similarly, the present final lined-up the two sprinters who have the most extreme step lengths that have ever been recorded for sub-10 s sprinters: the longest steps for Bolt with 2.70 m and the shortest for Su Bingtian with 2.26 m. Indeed, elite sprinters show up with a variety of body sizes and movement characteristics, and organise themselves to optimise the parameters that could affect performance. Here is the range for sprinters at 10.00 or faster:

- Body height: 1.65 m (Trindon Holliday) – 1.96 m (Usain Bolt).
- Body mass: 67 kg (Mark Jelks) – 96 kg (Ryan Bailey).
- Average step length: 1.98 m (Trindon Holliday) – 2.44 m (Usain Bolt and Kemar Bailey-Coyle).
- Relative step length: 1.15 (Quentin Butler) – 1.30 (Mike Marsh).
- Average step rate: 4.13 Hz (Kemar Bailey-Coyle) – 5.05 Hz (Trindon Holliday).

The message for coaches is that although taller athletes have a slight advantage statistically, there is a place for any body type and style. The advent of Usain Bolt reinforced the myth of a trend having sprinters getting taller and taller through the ages but it should be debunked – the average height for the 20 sprinters among the world bests of the last two decades of the XIXth century whose body heights were known to be an average of 1.78 m, whereas for today the average height for the sub-10 s sprinters is 1.80 m. In fact, the question of body height has always been present in sporting circles, as a former world record holder wrote a century ago:

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*“Some of our great sprinters were men averaging nearly six feet (1.83 m), but in the last few years sprinting has been somewhat revolutionized, so that today we find that the majority of our short distance runners are men of rather small stature” – Duffey (1905).*

As far back as the XVIIIth century, there is a report of a sprint match with odds going to the tallest one, *“remarkably flout in his body proportions”* who eventually lost to the *“little dejected looking being”*, as *“there is no faith in appearances”* (Sporting Magazine, 1794).

### Remarks on asymmetry

Appearances also give the idea that the best sprinters run with harmonious and balanced moves. Yet, asymmetries were found in the motion of the finalists in London. As mentioned earlier, Bolt’s contact times were notably different with a longer contact for the left foot, and this can be explained by the fact that this foot touches down with the ground further away relative to his body’s centre of mass (Table 5), while this distance should be minimized (Mann, 2013). Figure 13 further illustrates what happens during the impulse, as the braking phase during his left foot contact is longer than his right. This leg motion asymmetry had been spotted in ground contact and step length during the 9.58 s world record race (JAAF, 2010), in a 9.79 s race in Saint-Denis (2009) (Vazel, 2011), in a 9.86 s race in Zagreb (2011) (Antekolović, 2013) and during a pre-Olympic training test in 2012 (Miracle body, NHK, 2012). Therefore, it can’t explain why Bolt ran slower in London. After all, Carl Lewis set the previous top speed record before Bolt in the Seoul Olympics in 1988 with 12.04 m/s, doing so with a left contact significantly shorter than his right contact, 0.081 s vs. 0.086 s (Hlina, 1990). However, the magnitude of the difference between left and right legs found in Bolt in London was larger than what was reported in previous studies. Symmetry was an objective fitness assessment in the XIXth century when it was easy to measure step length from foot prints on clay or cinder track, long before the generalisation of rubber surfaces. A pioneer mile record holder, Walter George, was the first to report use of it in his training:

*“Several measurements at different parts of the track should be taken during the ordinary practice spins, and these must be carefully compared. Should they be found accurate and alike, day by day, you may be quite sure that you are running well and in your best form; should, however, they be short or irregular, there is surely something wrong.” – (George, 1902).*

It is beyond the scope of this report to enter into medical considerations, however Bolt’s scoliosis, leg length discrepancy and injury history are known within the public domain (L’Equipe magazine, 2012). In fact, his left leg has caused major concern during his career, with an Achilles injury that cut short his 2010 season and during the relay in London for his farewell race with a *“tear of the proximal myotendinous junction of biceps femoris in left hamstring with partial retraction”* (Bolt,

2017). According to Dan Pfaff, coach to former world record holder and Olympic champion Donovan Bailey, “*every athlete is asymmetrical; our job is to determine their bandwidth for efficiency and intervene when they are outside that bandwidth*” (Athletigen ACP conference, 2018).

### Which angles are meaningful to the coach?

Regarding body positions, the biggest asymmetry in Bolt is found at touchdown in the angle between his two thighs in terms of flexion and extension. Indeed, at touchdown (Figure 17; Table 10), his swing leg (right) is behind the left leg when the foot touches the ground, while when the right foot touches the ground, his left leg is ahead. How close the knee of the swing leg is from the knee of the contralateral leg at touchdown has long been seen as a key performance indicator for efficient sprinting in kilograms of the world’s fastest men in the Soviet literature (Kornelyuk, 1978; Maslakov, 1981; Levchenko, 1987, 1990; Breizer, 1989). Dyson (1962) noted that “*the mass of the leg is brought closer to the hip axis, reducing the leg’s moment of inertia and increasing velocity*”. It also affects the contralateral leg’s work according to Piasenta (1988) as when the swing leg is too far behind the vertical axis, “*the free limb is not in a favourable position to contribute to relieve the work of the impulse leg*”. Furthermore, Kunz (1981) found that smaller thigh angle ( $\eta$ ) is associated with a decrease in contact time and thus to increase sprinting speed. Yet, in the present report, shorter contact times seem to be less a consequence of a smaller thigh angle ( $\eta$ ) than a shorter horizontal distance from the point of ground contact to the body’s centre of mass at touch down (Table 5). However, it is not uncommon to watch sprinters having a negative thigh angle at training or warm-up and not doing it in competition. It is also interesting to notice that the biggest thigh angle ( $\eta$ ) was found in gold and silver medallists Gatlin and Coleman, showing one more time that even the most solid and verified key performance indicators can be challenged by successful individuals. Indeed, performance cannot depend on a single factor and rather always is a product of several factors that interplay and compensate each other. As statistically important is thigh angle ( $\eta$ ), coaches should be cautious not to pursue a path that would reduce it to the detriment of other factors.

A high knee lift has long been seen as a major marker of good sprinting performance, which probably dates back to the Ancient Greeks and the difference of style in sprinters (stadion) and distance runners (dolichos) as depicted in Panathenaic amphoras in the IVth and IIIrd Century B.C. However, higher knee lift in the fastest sprinters is not supported by the findings of 2017 100 m final, where angles  $\zeta$  (angle of the thigh and the vertical axis) and  $\delta$  (angle of hip flexion, thigh-torso) were not that different in medallists compared to the other finalists. This is also in line with the 1991 and 2007 WC reports (Ito, 1994, 2009), where there was no association between knee

lift angle and maximum running velocity, and also with the extensive work led by Prof. Zatsiorsky in the late 1970s on 107 Soviet sprinters from world to national class (Tjupa et al., 1978). A more important feature to watch is the knee flexion at stance (Table 14) where the medallists in London managed to maintain knee angle compared to the other finalists, meaning that the angle should be the highest, confirming previous findings during 1991 WC (Ito, 1994, 1998). Inversely, the knee angle at toe-off ( $\beta$ ) should be the smallest, as the 2017 findings back up those of 1991, 1997, 2007 WC (Ito, 1994, 2009; Kersting, 1999; Ryu, 2011). A full extension of the knee was seen as a picture of good technique until Zatsiorsky's work, which found that extending the knee over  $165^\circ$  required supplementary muscular work and time, while no longer applying significant force into the ground. In London's finalists, the mean  $\beta$  angle was  $154^\circ$ , slightly smaller than the same angle at touchdown. This is a useful and simple marker for the coach in order to assess proper technique, in short sprints as well as sprinting under fatigue as shown in London 2017's 400 m commentaries.

#### The path from Junior to lifetime best

A more efficient technique and greater strength result in more forces being applied to the ground in the proper direction and in a shorter time. Consequently, both step length and frequency should be improved, however, since step length depends largely on leg length, a constant parameter, most of the running velocity improvement is a result step frequency. This is illustrated by the comparison between mean step length and frequency for the finalists' result in London 2017 WC and their personal best.

Athlete	Time (s)		Step length (m)		Step frequency (Hz)	
	PB	WC 2017	PB	WC 2017	PB	WC 2017
<b>GATLIN</b>	9.74	9.92	2.30	2.27	4.46	4.44
<b>COLEMAN</b>	9.82	9.94	2.13	2.13	4.79	4.72
<b>BOLT</b>	9.58	9.95	2.44	2.44	4.28	4.12
<b>BLAKE</b>	9.69	9.99	2.19	2.17	4.72	4.60
<b>SIMBINE</b>	9.89	10.01	2.09	2.08	4.84	4.77
<b>VICAUT</b>	9.86	10.08	2.21	2.13	4.59	4.60
<b>PRESCOD</b>	10.03	10.17	2.27	2.27	4.37	4.33
<b>SU</b>	9.99	10.27	2.08	2.08	4.80	4.67

For most of them, the running velocity loss was due to a lower step frequency, with the exception of Vicaut, who was recovering from a leg injury. Comparison with performance as teenagers gives

useful markers to the coach (Vazel, 2008) and the study on London's finalists confirms this trend towards a larger improvement in step frequency, i.e., quicker ground contact, producing enough force in the proper direction to increase or at least maintain step length.

Athlete (age)	Time (s)		Step length (m)		Step frequency (Hz)	
	Teen	PB	Teen	PB	Teen	PB
<b>GATLIN (19)</b>	10.08	9.74	2.35	2.30	4.23	4.46
<b>COLEMAN (18)</b>	10.30	9.82	2.18	2.13	4.46	4.79
<b>BOLT (15)<sup>§</sup></b>	10.57	9.58	2.25	2.44	4.21	4.28
<b>BLAKE (16)</b>	10.34	9.69	2.17	2.19	4.45	4.72
<b>SIMBINE (19)</b>	10.38	9.89	2.04	2.09	4.72	4.84
<b>VICAUT (18)</b>	10.29	9.86	2.18	2.21	4.45	4.59
<b>PRESCOD</b>	<i>No data</i>					
<b>SU (19)</b>	10.28	9.99	2.08	2.08	4.67	4.80

<sup>§</sup> Data for the first 100 m (in bend) of a 200 m race, as Bolt didn't take part in 100 m races in his early years.

Interestingly, from junior to senior level for Gatlin and Coleman, step frequency improvement was made at the expense of step length, which is a rare occurrence. The opposite is equally very rare, and significant drop in step frequency compensated by huge gains in step length has only been recorded in sub-10 s runners James Dasaolu (PB 9.91 in 2013) and Lerone Clarke (PB 9.99 in 2012), through technical and relaxation enhancements. Statistically, the improvement ratio is 2/3 for step frequency and 1/3 for step length in the path from u20 category to lifetime best. However, the finalists of the 2017 edition showed once again that elite sport is made of exceptions. Biomechanical reports offer objective markers to scale their strengths and weaknesses, using laws of mechanics, as well as data from other athletes and screening a given athlete's progress over time. It's up to the coach to embrace the general trends derived from large number of subjects and draw a career progression taking in account the unique traits that each sprinter has.

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## Coaching commentary – Ralph Mouchbahani

The data obtained from the world championships in London confirm the current model that is taught and used in the IAAF CECS programme. It appears that the difference between the performance of podium finishers and the other finalists, and indeed the finalists and non-finalists, is based on the ability to generate the highest horizontal velocity of the centre of mass throughout the key phases of the race. Further, it also appears that having a faster leg cycle and the maintenance of short ground contact times appear to be key.

Fifth placed Akani Simbine only missed out on a medal because of difficulties in the transition phase, i.e., from acceleration to maximal velocity and from maximal velocity to maintenance. All three medallists were able to maintain minimal reductions in velocity between the transitions, allowing them to keep a smooth overall velocity.

	CM horizontal velocity (m/s)	± average (%)
<b>GATLIN</b>	11.61	+0.26
<b>COLEMAN</b>	11.66	+0.69
<b>BOLT</b>	11.75	+1.47
<b>BLAKE</b>	11.59	+0.09
<b>SIMBINE</b>	11.62	+0.35
<b>VICAUT</b>	11.54	-0.35
<b>PRESCOD</b>	11.55	-0.26
<b>SU</b>	11.35	-1.99
<b>Average</b>	11.58	

During analysis of the mid-point of the race, Yohan Blake was the only athlete from the top 5 finishers with a horizontal CM velocity below 11.60 m/s. Despite this, he was still above the average velocity at this stage. He seems to compensate for less speed with stride length. Looking at the velocities of the stride generated, it is interesting to note that Justin Gatlin is the only medallist that clearly generates drive through push (stride length) rather than step frequency. Alternatively, Christian Coleman has the shortest stride, relative to the other two medallists. This is because of his height and compensates with an increased stride frequency. The balance between optimal stride length, stride rate and velocity of the centre of mass will generate the greatest driving velocities, seen in Table 9. The recovery velocity of the leg is strongly related to the angle of the knee joint (i.e., heel close underneath the buttocks). Pairing active knee velocity

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and driving velocity generates the greatest overall mean velocity, expressed here through the centre of mass velocity.

### Recommendations for practice

#### 1. Drills for acceleration

- Push 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 speed 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 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.

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## CONTRIBUTORS

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