Kinematic and Kinetic Comparisons of Elite and Well-Trained Sprinters During Sprint Start

Jean Slawinski,[1] Alice Bonnefoy,[1] Jean-Michel Levêque,[1] Guy Ontanon,[1] Annie Riquet,[1] Raphaël Dumas,[2] and Laurence Chèze[2]

[1]*Scientific Expertise Centre, TeamLagardere, Jean Bouin Stadium, Paris, France; and* [2]*University of Lyon 1, Laboratory of Biomechanics and Mechanics of Shocks, Villeurbanne, France*

Abstract

Slawinski, J, Bonnefoy, A, Levêque, JM, Ontanon, G, Riquet, A, Dumas, R, and Chèze, L. Kinematic and kinetic comparisons of elite and well-trained sprinters during sprint start. *J Strength Cond Res* 24(4): 896–905, 2010—The purpose of this study was to compare the main kinematic, kinetic, and dynamic parameters of elite and well-trained sprinters during the starting block phase and the 2 subsequent steps. Six elite sprinters (10.06–10.43 s/100 m) and 6 well-trained sprinters (11.01–11.80 s/100 m) equipped with 63 passive reflective markers performed 4 maximal 10 m sprint starts on an indoor track. An optoelectronic motion analysis system consisting of 12 digital cameras (250 Hz) was used to record 3D marker trajectories. At the times "on your marks," "set," "clearing the block," and "landing and toe-off of the first and second step," the horizontal position of the center of mass (CM), its velocity (XCM and VCM), and the horizontal position of the rear and front hand (X_{Hand_rear} and X_{Hand_front}) were calculated. During the pushing phase on the starting block and the 2 first steps, the rate of force development and the impulse ($F_{impulse}$) were also calculated. The main results showed that at each time XCM and VCM were significantly greater in elite sprinters. Moreover, during the pushing phase on the block, the rate of force development and $F_{impulse}$ were significantly greater in elite sprinters (respectively, 15,505 ± 5,397 $N{\cdot}s^{-1}$ and 8,459 ± 3,811 $N{\cdot}s^{-1}$ for the rate of force development; 276.2 ± 36.0 N·s and 215.4 ± 28.5 N·s for $F_{impulse}$, $p \le 0.05$). Finally, at the block clearing, elite sprinters showed a greater X_{Hand_rear} and X_{Hand_front} than well-trained sprinters (respectively, 0.07± 0.12 m and −0.27 ± 0.36 m for X_{Hand_rear}; 1.00 ± 0.14 m and 0.52 ± 0.27 m for X_{Hand_front}; $p \le 0.05$). The muscular strength and arm coordination appear to characterize the efficiency of the sprint start. To improve speed capacities of their athletes, coaches must include in their habitual training sessions of resistance training.

Key Words running, motion analysis, performance training

Introduction

The analysis of different 100 m finals of international events (Olympic Games in Seoul 1988, World Championships in Tokyo 1991, Athens 1997, Seville 1999, and Osaka 2007; from International Association of Athletics Federations reports) demonstrated that sprinters reached a maximal velocity of 11.67 $m{\cdot}s^{-1}$ between the 50 m and 60 m of the race. This analysis also demonstrated that, during the first 10 m, the speed gain is maximal: 8.15 $m{\cdot}s^{-1}$ at 10 m. More recently, during the last Olympic games in Beijing, the spectacular run of Usain Bolt in the Bird's Nest confirmed this analysis. Indeed, Bolt finished in 9.69 seconds, reaching an amazing maximal velocity of about 12.2 $m{\cdot}s^{-1}$ between 40 m and 50 m of the run (13) with a very small number of strides (only 40 compared with the 44 used by the rest of the field). During the first 10 m of the sprint, the speed gain was also maximal: 9.05 $m{\cdot}s^{-1}$ at 10 m. Thus, to reach a higher maximal velocity, we see that the starting block phase and subsequent acceleration phase are 2 extremely important phases, which directly generate the results in a 60 m and 100 m sprint.

Many authors have been interested in the biomechanical factors of these 2 phases to explain the key factors of sprint performance (7–9,11,16,18–20,24,25). The starting block phase refers to the time during which the sprinter is in contact with the blocks (24). A closer horizontal projection of the center of mass (CM) in the "set position" to the starting line and a shorter block time guarantee a maximal block velocity of the sprinter (9). The subsequent acceleration refers to the first step until the 10th m of the run (10). The efficiency of this phase depends on the execution of the first step, particularly the length of the step and the position of the foot in the contact phase. In the first 3 steps, the body's CM has to

Address correspondence to Jean Slawinski, jean.slawinski@teamlagardere.com.

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rise gradually in a vertical direction to enable the maximization of the anterior component of velocity of the CM (9).

However, even though numerous kinematics studies have covered the subject of the sprint start, little data have been published for elite sprinters. Nevertheless, detailed information on the starting block phase and on the first meters of the run could be of great importance for coaches to better understand the specific movements of both these phases and to develop them. The purpose of this study was to compare the major kinematic and kinetic parameters of elite and well-trained sprinters during these phases of the sprint start. This analysis will describe the most relevant kinematic and kinetic parameters that contribute positively to the efficiency of the block phase and the subsequent acceleration in elite sprinters.

Methods

Experimental Approach to the Problem

Six elite sprinters and 6 well-trained sprinters performed 4 maximal 10 m sprint starts on an indoor track (Figure 1). The sprinters started the run using starting blocks. All trials were used for further analysis.

Subjects

The sprinters gave their informed written consent to participate in the study. Their age, body mass, height, and personal best times over 100 m are presented in the Table 1. Performance times of the elite sprinters over 100 m ranged between 10.06 and 10.43 seconds. This group was called "elite" because each had already participated in an international competition and belongs to the group of the 20 best French sprinters. This study conforms to the recommendations of the Declaration of Helsinki and was approved by the local ethics committee.

Procedures

The reaction time (RT) was measured with Reactime (Microgate, Bolzano, Italy). The time at 5 m and 10 m (T5 and T10) was recorded using photocells (Microgate, Bolzano, Italy).

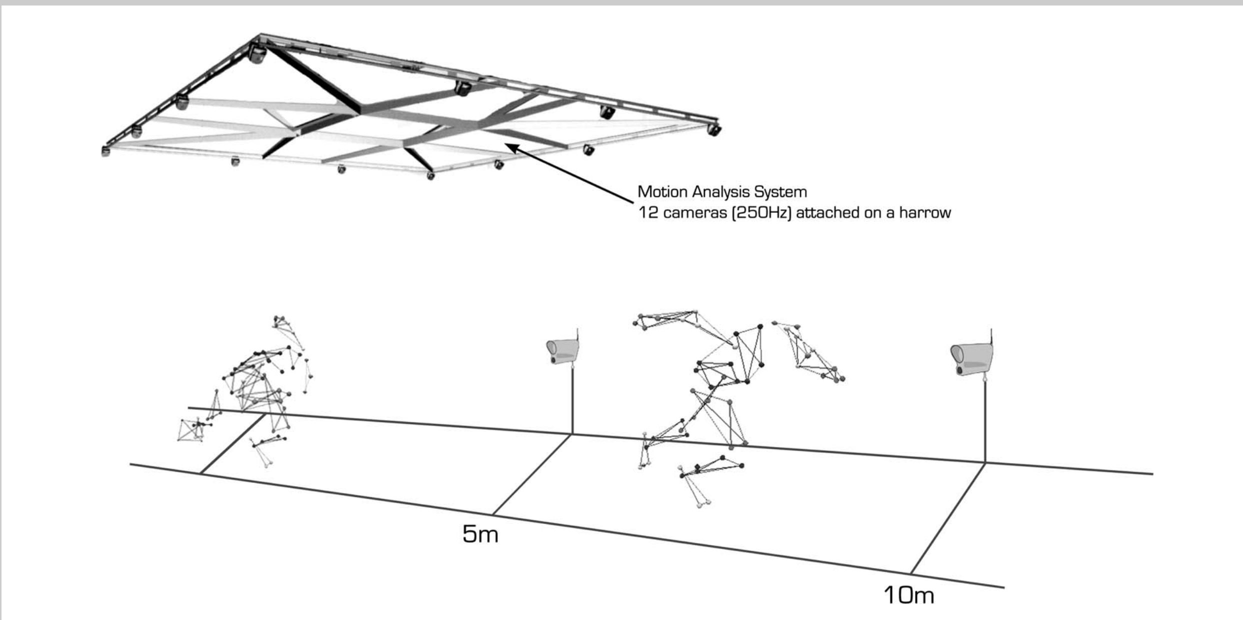

Figure 1. Experimental design.

Table 1. Characteristics of sprinters.

	Height (cm)	Weight (kg)	Age (yr)	Half squat, max force (N)	100-m time (s)
Elite sprinters (±*SD*)	179.2 ± 6.2	79.5 ± 10.5	24.5 ± 3.2	2,192 ± 145	10.27 ± 0.14
Well-trained sprinters (±*SD*)	175.3 ± 4.0	66.3 ± 5.5†	21.3 ± 3.0	1,845 ± 69*	11.31 ± 0.28*

*$p \leq 0.0001$.
†$p \leq 0.05$.
‡Half squat maximal force was measured with isokinetic ergometer from Ariel Dynamics, Inc. (Trabucco Canyon, CA < USA).

An opto-electronic motion analysis system (Santa Rosa, CA, USA) consisting of 12 digital cameras (250 Hz) was used to record the 3D marker trajectories. The subject was equipped with 63 passive reflective markers (16 mm diameter) (Figure 2). The markers were glued to the skin and were assumed to follow the movement of the bony landmarks. The markers have to be placed on points that are easily identifiable on all participants, as close as possible to the bony parts of the landmarks. This is required to minimize the influence of the soft tissues that may result in movement errors by way of the skin and fat tissues. The 3D trajectories of the passive reflective markers were computed and then corrected by a low-pass filter (Butterworth, fourth-order, with a cut-off frequency of 8 Hz). Three coordinate systems were determined on each body segment based on the markers. The orientation of their axes was carefully carried out using ISB recommendations (31,32). The rotation sequences proposed by the International Society of Biomechanics (ISB) were used to describe the lower- and the upper-limb joint movements.

The RT and the Time at 10 m Were Used to Compute the Velocity of the Sprinter. Segment kinematics during the starting block phase (defined as the phase during which at least 1 foot is in contact with the starting block) and the 2 first steps of the acceleration phase were reconstructed from the spatial trajectories of the markers according to ISB recommendations. Angle values presented in this study correspond to the instantaneous rotation value about the *z*-axis (i.e., angles of flexion-extension). Moreover, from the reconstructed spatial trajectories of the

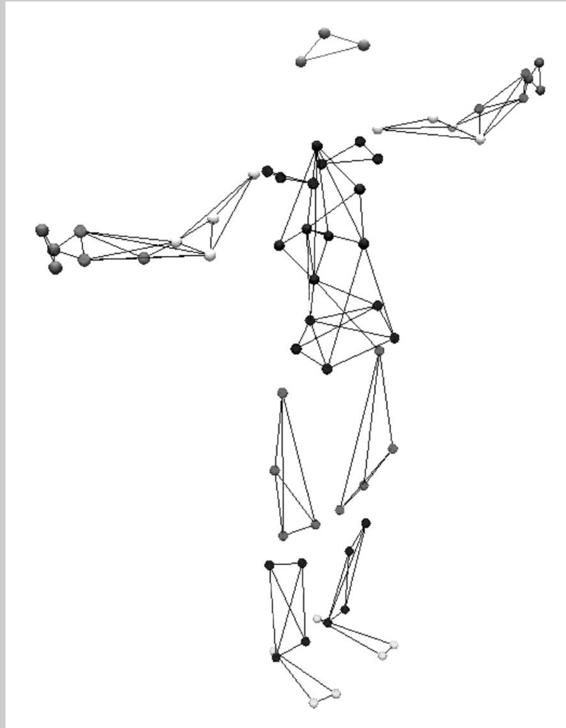

Figure 2. Body modelled with 63 passive reflective markers.

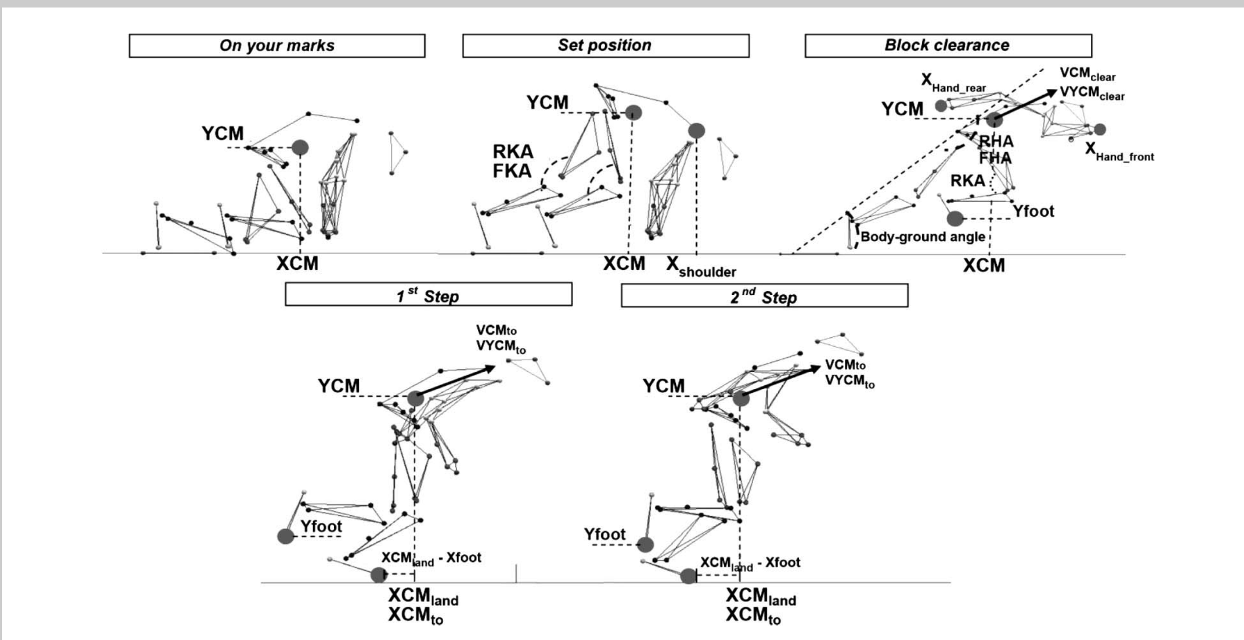

Figure 3. Five critical instants used to analyse kinematics data.

markers, the segment mass, position of the CM, and inertia tensor were estimated with scaling equations (12).

To analyse the movement of the athletes, 3 critical phases were identified during the block phase (on your mark, set position, and block clearing), and the first and the second steps were used to describe the acceleration phase (Figure 3). For each phase, different kinematics and kinetics parameters were calculated using Matlab (Mathworks, Natick, MA, USA) and Excel software (Microsoft, Redmond, WA, USA). The referential origin was placed on the middle of the start lane.

Position "On Your Marks". Vertical and anterior components of the CM (YCM and XCM) were calculated.

Position "Set". YCM and XCM, anterior-posterior position of the shoulder ($X_{shoulder}$), and front and rear knee flexion-extension angles (FKA and RKA) were calculated.

Clearing of the Block. This phase refers to the time when the front foot leaves the starting block. We measured YCM and XCM, the anterior-posterior position of the rear and front hand (X_{Hand_rear} and X_{Hand_front}), the 2D angle between the ground and the body and the flexio-n-extension of the rear and front hip (RHA and FHA), and RKA. The term "rear" refers to the side of the body that is associated with the rear foot in the blocks. The term "front" refers to the side of the body that is associated with the front foot in the blocks. The vertical velocity and the norm of the velocity of the CM were also calculated on clearing the block ($VYCM_{clear}$ and VCM_{clear}). All these parameters are detailed in Figure 3.

To characterize the efficiency of the block phase, we took into account a pushing phase. This phase comprises the time from the first movement of the set position to the clearing block. We measured the duration of this phase (time block), the pushing time on the rear block (PTRB), the percentage of the pushing time on the rear block (%PTRB), the time flight between the rear block and the first step (T_{f_rear} block to

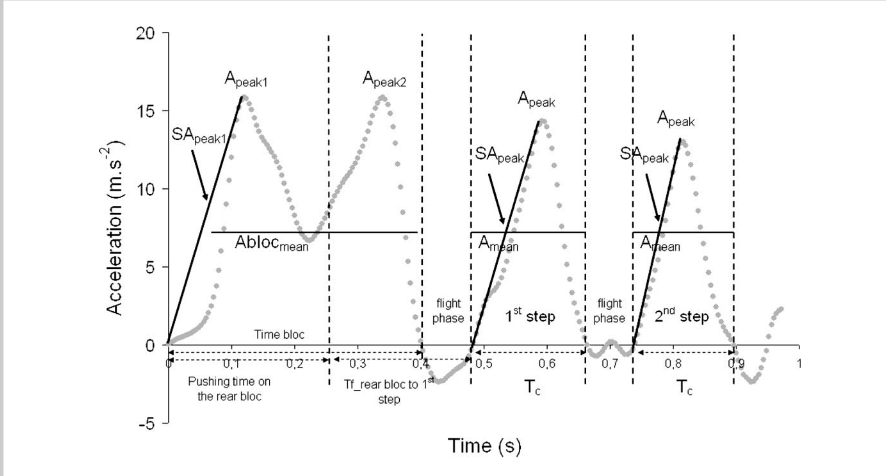

Figure 4. Typical acceleration of center of mass (CM) curve during block phase, first and second step.

Table 2. Kinematic and kinetic data for center of mass during "on your marks position."*

On your marks position	Elite sprinters (±*SD*)	Well-trained sprinters (±*SD*)
XCM (cm)	−25.7 ± 2.1	−31.7 ± 4.5†
YCM (cm)	49.7 ± 3.1	51.3 ± 5.4

*XCM = anterior component of center of mass; YCM = vertical component of center of mass.
†$p \leq 0.05$.

Table 3. Kinematic and kinetic data for center of mass during "set position."*

Set position	Elite sprinters (±*SD*)	Well-trained sprinters (±*SD*)
XCM (cm)	−22.9 ± 1.5	−27.81 ± 2.8†
YCM (cm)	65.7 ± 3.8	62.6 ± 3.9
Xshoulder (cm)	10.7 ± 2.7	4.0 ± 5.5†
Front knee angle (°)	110.7 ± 9.3	106.1 ± 13.7
Rear knee angle (°)	135.5 ± 11.4	117.3 ± 10.1†

*XCM = anterior component of center of mass; YCM = vertical component of center of mass; Xshoulder = anterior-posterior position of shoulder.
†$p \leq 0.05$.

first step), the average speed and acceleration of the CM during the pushing phase ($Vblock_{Mean}$, $Ablock_{Mean}$), the first and second peak acceleration (A_{peak1}, A_{peak2}), and the rate of force development (RFD). The RFD was calculated as the product between the slope of the first acceleration (SA_{peak1}) and the body mass. The average force impulse ($F_{impulse}$) was also calculated. $F_{impulse}$ is the product of the resultant force applied on the ground and the duration of application of this force. In other words, $F_{impulse}$ is the integral of the resultant force applied on the ground during the block phase. Thus, we calculated $F_{impulse}$ as

Table 4. Kinematic and kinetic data for center of mass during "pushing phase."*

Block phase	Elite sprinters ($\pm SD$)	Well-trained sprinters ($\pm SD$)
Time block (s)	0.352 ± 0.018	0.351 ± 0.020
PTRB (s)	0.154 ± 0.017	0.140 ± 0.026
%PTRB (s)	43.5 ± 3.8	39.8 ± 8.1
T_f_rear block to first step (s)	0.292 ± 0.021	0.300 ± 0.029
$Vblock_{Mean}$ ($m \cdot s^{-1}$)	1.94 ± 0.09	1.87 ± 0.14
$Ablock_{Mean}$ ($m \cdot s^{-2}$)	9.5 ± 0.4	8.8 ± 0.8
A_{peak1} ($m \cdot s^{-2}$)	16.7 ± 1.9	13.7 ± 3.1
A_{peak2} ($m \cdot s^{-2}$)	13.6 ± 1.8	12.6 ± 1.3
RFD ($N \cdot s^{-1}$)	15505 ± 5,397	8459 ± 3,811†
$F_{impulse}$ ($N \cdot s$)	276.2 ± 36.0	215.4 ± 28.5†

*PTRB = pushing time on rear block; T_f_rear block to first step = time flight between rear block and first step; $Vblock_{Mean}$ = average speed of center of mass during pushing phase; $Ablock_{Mean}$ = acceleration of center of mass during pushing phase; A_{peak1} = first peak acceleration; A_{peak2} = second peak acceleration; RFD = rate of force development; $F_{impulse}$ = average force impulse.
†$p \leq 0.05$.

$$F_{impulse} = \int_0^t Fdt \text{ where } F = (F_y - P) + F_x + F_z$$

$$F_{impulse} = M \int_0^t \gamma dt$$

$$F_{impulse} \approx VCM_{clear} \times M \qquad \text{eq.1}$$

In this equation, F is the norm of the resultant reaction force applied on the ground (F_y, F_x, and F_z are the vertical, horizontal, and lateral components of the resultant force), P is the weight, γ is the norm of the resultant acceleration of the CM, VCM_{clear} is the norm of the velocity of the CM at the block clearing (calculated with the motion analysis system), and M is the body mass.

First and Second Step. We calculated the anterior component of the CM when the foot hit the ground (XCM_{land}), the anterior component of the CM when the foot left the ground (XCM_{to}), the distance travelled by the CM during stance (DCM), the difference between the anterior-posterior position of the foot when the foot hit the ground and XCM_{land} ($XCM_{land} - X_{foot}$), the highest vertical position of the free foot (Y_{foot}), the velocity norm and the vertical velocity of the CM at the toe-off (VCM_{to}, $VYCM_{to}$), the time contact (T_c), the time flight between the block clearing and the first step (T_f - Block to first step), and the time flight between the first step and the second step (T_f - first to second step). During stance, we also calculated the average velocity of the CM (V_{mean}), the average and maximal acceleration of the CM (A_{mean} and A_{max}), the slope of the first acceleration (SA_{max}) and the RFD (Figure 4), the stride rate (SR), and the stride length (SL).

Statistical Analyses

All data are presented as means plus or minus *SD*. After a normality test, comparison of the kinematics and kinetics

Table 5. Kinematic and kinetic data for center of mass during "block clearing."*

Clearing of block	Elite sprinters ($\pm SD$)	Well-trained sprinters ($\pm SD$)
XCM (cm)	37.0 ± 2.0	30.2 ± 5.9†
YCM (cm)	82.8 ± 3.3	81.2 ± 4.1
Y_{foot} (cm)	22.9 ± 4.2	19.1 ± 4.5
VCM_{clear} ($m \cdot s^{-1}$)	3.48 ± 0.05	3.24 ± 0.18†
$VYCM_{clear}$ ($m \cdot s^{-1}$)	0.52 ± 0.06	0.51 ± 0.14
XHand_rear (cm)	7.5 ± 12.0	−27.1 ± 36.5†
XHand_front (cm)	99.8 ± 13.8	52.3 ± 27.0†
RKA (°)	−97.5 ± 7.0	−82.1 ± 10.2†
Body - ground angle (°)	34.7 ± 1.4	34.3 ± 2.0
RHA (°)	79.3 ± 8.8	73.7 ± 11.0
FHA (°)	171.2 ± 8.4	173.1 ± 12.5

*XCM = anterior component of center of mass; YCM = vertical component of center of mass; Y_{foot} = highest vertical position of free foot; VCM_{clear} = norm of velocity of center of mass; $VYCM_{clear}$ = vertical velocity of center of mass; XHand_rear = horizontal position of rear hand; XHand_front = horizontal position of front hand; RKA = rear knee flexion-extension angle; RHA = flexion-extension of rear hip; FHA = flexion-extension of front hip.
†$p \leq 0.05$.

Table 6. Kinematic and kinetic data for center of mass during "first step."*

First step	Elite sprinters ($\pm SD$)	Well-trained sprinters ($\pm SD$)
XCM_{land} (cm)	68.5 ± 4.7	58.0 ± 8.1†
XCM_{to} (cm)	137.1 ± 9.0	120.8 ± 8.7†
DCM (cm)	68.6 ± 5.1	62.8 ± 4.4
Y_{foot} (cm)	22.7 ± 8.6	32.7 ± 6.7†
VCM_{to} ($m \cdot s^{-1}$)	4.69 ± 0.15	4.42 ± 0.11†
$VYCM_{to}$ ($m \cdot s^{-1}$)	0.35 ± 0.03	0.42 ± 0.09
$XCM_{land} - X_{foot}$ (cm)	17.5 ± 3.0	19.4 ± 4.5
T_c(s)	0.173 ± 0.010	0.167 ± 0.011
T_f − Block to first step (s)	0.093 ± 0.009	0.087 ± 0.021
T_f − first to second step (s)	0.067 ± 0.008	0.083 ± 0.031
V_{Mean} ($m \cdot s^{-1}$)	4.06 ± 0.09	3.87 ± 0.12†
A_{Mean} ($m \cdot s^{-2}$)	7.5 ± 0.4	7.0 ± 0.4
A_{max} ($m \cdot s^{-1}$)	15.2 ± 1.3	13.6 ± 2.3
RFD ($N \cdot s^{-1}$)	13,570 ± 4,126	9,804 ± 2287
SR (Hz)	3.78 ± 0.24	3.97 ± 0.34
SL (cm)	137.1 ± 9.0	120.8 ± 8.7†
$F_{impulse}$ ($N \cdot s$)	104.8 ± 16.5	78.6 ± 6.3†

*XCM_{land} = anterior component of center of mass when foot hit the ground; XCM_{to} = anterior component of center of mass when foot left the ground; DCM = distance travelled by center of mass during stance; Y_{foot} = highest vertical position of free foot; VCM_{to} = vertical velocity of center of mass at toe-off; $VYCM_{to}$ = vertical velocity of center of mass at toe-off; $XCM_{land} - X_{foot}$ = difference between the anterior-posterior position of foot when foot hit the ground; T_c = time contact; T_f − Block to first step = time flight between block clearing and first step; T_f − first to second step = time flight between first step and second step; V_{Mean} = average velocity of center of mass; A_{Mean} = average acceleration of center of mass; A_{max} = maximal acceleration of center of mass; RFD = rate of force development; SR = stride rate; SL = stride length; $F_{impulse}$ = average force impulse.

†$p \leq 0.05$.

data between the elite and well-trained sprinters was performed with an unpaired Student's *t*-test. All significant differences reported are at $p \leq 0.05$ unless otherwise noted.

Results

Reaction Time and Time at 5 and 10 Meters

The average RT of the elite sprinters was not significantly different from that of the well-trained sprinters (respectively, 0.151 ± 0.016 s vs. 0.158 ± 0.033 s; $p = 0.7$). When the time at 5 m and 10 m minus the RT was considered, the elite sprinters ran faster than the well-trained sprinters: the times at 5 m and 10 m were, respectively, 1.20 ± 0.04 seconds and 1.88 ± 0.03 seconds for the elite sprinters and 1.25 ± 0.03 seconds and 1.97 ± 0.05 seconds for the well-trained sprinters ($p \leq 0.05$). When the total time was considered, only the time at 10 m was lower for elite sprinters (2.03 ± 0.04 s vs. 2.12 ± 0.06 s; $p \leq 0.05$). The average velocity at 10 m was also higher for elite sprinters (4.93 ± 0.09 vs. 4.71 ± 0.14 $m \cdot s^{-1}$; $p \leq 0.05$).

Kinematics and Kinetics

All results are presented in Tables 2, 3, 4, 5, and 6 and Figures 4 and 5. In the position "on your marks," XCM was greater in elite sprinters (Table 2). In the "set position," XCM, $X_{shoulders}$, and RKA of the elite sprinters were greater than those of the well-trained sprinters (Table 3). During the pushing phase on the block, only the RFD and $F_{impulse}$ were greater in the elite sprinters (Table 4). At the clearing of the block, XCM and VCM_{clear} were greater in elite sprinters (Table 5). The elite sprinters positioned their rear and front hands closer to the finish line than the well-trained sprinters. During the first step, XCM_{land}, XCM_{to}, VCM_{to}, V_{Mean}, $F_{impulse}$, and SL were greater in the elite sprinters (Table 6). Table 7 shows that XCM_{to}, VCM_{to}, and $F_{impulse}$ were greater in the elite sprinters and that $VYCM_{to}$ was lower in the elite sprinters.

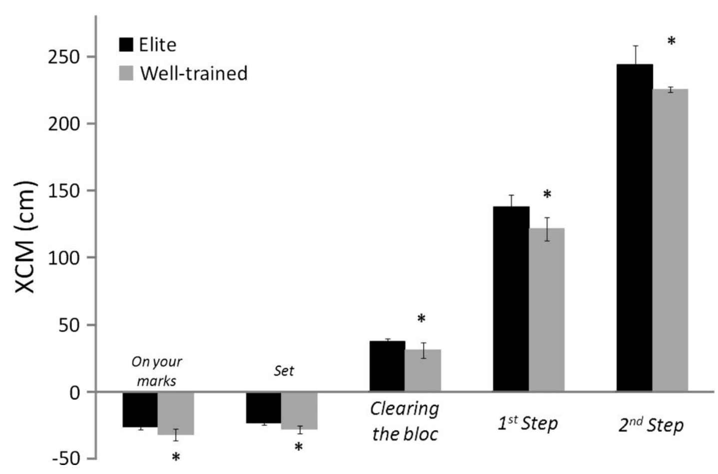

Figure 5. Horizontal position of center of mass (XCM) at 5 critical instants (*$p \leq 0.05$).

TABLE 7. Kinematic and kinetic data for center of mass during "second step."*

Second step	Elite sprinters (±*SD*)	Well-trained sprinters (±*SD*)
XCM_{land} (cm)	168.2 ± 11.3	156.9 ± 12.4
XCM_{to} (cm)	243.6 ± 13.9	224.9 ± 12.0†
DCM (cm)	75.3 ± 5.72	68.4 ± 7.9
Y_{foot} (cm)	24.4 ± 6.2	26.7 ± 7.2
VCM_{to} ($m \cdot s^{-1}$)	5.50 ± 0.26	5.25 ± 0.13†
$VYCM_{to}$ ($m \cdot s^{-1}$)	0.35 ± 0.05	0.45 ± 0.07†
$XCM_{land} - X_{foot}$ (cm)	6.1 ± 4.6	7.3 ± 9.0
T_c (s)	0.138 ± 0.031	0.145 ± 0.016
V_{Mean} ($m \cdot s^{-1}$)	5.07 ± 0.19	4.84 ± 0.09†
A_{Mean} ($m \cdot s^{-2}$)	6.2 ± 0.5	5.6 ± 1.2
A_{max} ($m \cdot s^{-1}$)	13.8 ± 2.8	12.7 ± 5.9
RFD ($N \cdot s^{-1}$)	12,172 ± 3,494	10,092 ± 1,069
SR (Hz)	4.61 ± 0.16	4.40 ± 0.27
SL (cm)	106.6 ± 5.9	105.3 ± 6.3
$F_{impulse}$ (N·s)	75.0 ± 15.8	55.9 ± 9.4†

*XCM_{land} = anterior component of center of mass when foot hit the ground; XCM_{to} = anterior component of center of mass when foot left the ground; DCM = distance travelled by center of mass during stance; Y_{foot} = highest vertical position of free foot; VCM_{to} = vertical velocity of center of mass at toe-off; $VYCM_{to}$ = vertical velocity of center of mass at toe-off; $XCM_{land} - X_{foot}$ = difference between the anterior-posterior position of foot when foot hit the ground; T_c = time contact; T_f − Block to first step = time flight between block clearing and first step; T_f − first to second step = time flight between first step and second step; V_{Mean} = average velocity of center of mass; A_{Mean} = average acceleration of center of mass; A_{max} = maximal acceleration of center of mass; RFD = rate of force development; SR = stride rate; SL = stride length; $F_{impulse}$ = average force impulse.
†$p \leq 0.05$.

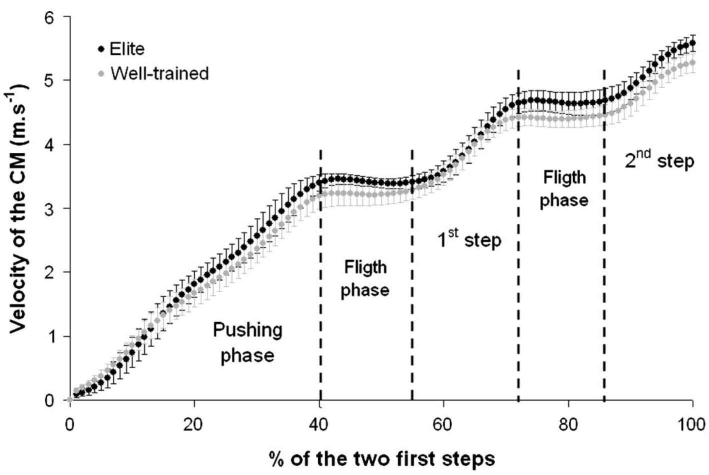

Figure 6. Evolution of velocity of center of mass during pushing phase and 2 first steps.

DISCUSSION

The above results show that the elite sprinters started faster than the well-trained sprinters. At 5 m, the elite sprinters, compared with the well-trained sprinters, had a gain of 0.05 seconds and a gain of 0.09 seconds at 10 m. This means that the well-trained sprinters would be 44 cm behind the elite sprinters at the 10 m mark. Moreover, the comparison of the present data with the time at 10 m performed during international events (the Olympic Games in Seoul 1988, the World Championships in Tokyo 1991, Athens 1997, Seville 1999, and Osaka 2007) confirmed that the best sprinters started faster. The average time at 10 m of 17 sprinters with a time over 100 m of less than 10 seconds is 1.84 ± 0.06 seconds (including RT). This time at 10 m corresponds to an average speed of 5.44 ± 0.19 $m \cdot s^{-1}$, which is 110% greater than the 1 of the elite sprinters from this study. In other words, at the 10 m mark, the elite sprinters from our study would be 90 cm behind a sprinter with a personal best over 100 m of less than 10 seconds. More recently, the importance of the first 10 m in achieving a good performance during the 100 m race is confirmed by the work of Eriksen et al. (13), which modelled the race of Usain Bolt during his world record race. They found a time at the 10 m mark of 1.75 seconds (including RT), which corresponds to an average speed of 5.66 $m \cdot s^{-1}$. Thus, at the 10 m mark, the sprinters with a personal best over 100 m would be about 50 cm behind Usain Bolt.

These first 10 m are influenced by the RT and the first steps of the run. The study of the RT during international championships demonstrated that the RT is generally lesser than 0.2 seconds (between 0.12 and 0.17 s) and that it increases in proportion to the length of the race distance (2,14,22). The results of the present study demonstrate that the RT for elite and well-trained runners was, respectively, 0.151 seconds and 0.158 seconds, and no significant differences in RT existed between the 2 populations. This result was confirmed by

Mero et al. (24), who suggested that RT does not correlate with performance level. Other parameters (e.g., position or velocity of the CM) may be more important than RT in explaining the differences observed in the 5 m and 10 m times between the 2 populations. The kinematic and kinetic analysis allows us to understand better why the elite sprinters showed faster times at 5 m and 10 m than the well-trained sprinters.

The results of the present study show that elite sprinters put their CM closer to the start line than the well-trained sprinters (Figure 5). Positioning the CM as close as possible to the start line is important in reducing the distance by which the athlete must displace his CM and in creating a greater velocity of the CM during the pushing phase. Baumann (3) also found that the horizontal distance from the start line to the CM decreased with increasing performance level. Harland and Steele (18) confirmed these observations and found that the horizontal distance of the CM from the start line (XCM) was 0.16 m for fast (10.35 s), 0.20 m for medium (11.11 s), and 0.27 for slow sprinters (11.85 s). In the present study, we found a greater XCM for elite (0.23 m) and well-trained sprinters (0.28 m). These differences could be related to the method of calculation of the CM. In fact, in this study, we used new scaling equations (12) to compute the segment mass, the position of the CM . This greater XCM for elite sprinters is a result of a greater rear knee angle. Indeed, the elite sprinters, when compared with the well-trained sprinters, presented the same front knee angle but a greater rear knee angle. A greater rear knee angle allowed the sprinters to position the shoulders further forward and to move the CM closer to the start line. These data are confirmed by Harland and Steele (18), who summarized knee angles of skilled sprinters in the set position measured in different studies. They showed that the front knee angle in the set position ranges from 90° to 110°, and the rear knee angle ranges from 115° to 130°. This greater rear knee angle and the further forward position of the shoulder suggested that the strength of the arms is a key factor in reducing this horizontal distance from the start line to the CM. The stronger the arms are, the shorter the horizontal distance from the start line to the CM (24).

At the block clearing, the elite sprinters had greater XCM than well-trained sprinters (Figure 5). XCM depends on the position of the body segments (trunk, arms, legs, etc.). The results of this study showed that the elite runners placed both hands (front and rear) further forward than the well-trained sprinters (Table 5). Thus, for elite sprinters, the ability to move the CM further forward than well-trained sprinters depends partially on the movement of the arms. Many studies have investigated the coordination between legs and arms of explosive leg extensions movement such as squat jump (5,6,15,23). However, few studies have been interested in the analysis of arm movements in the sprint start (4,26). Bhowmick and Bhattacharyya (4) suggested only that the vertical component of the arm movement creates a favorable condition to improve the sprint start. However, more studies have to be conducted to better understand the role of the arms in the sprint start and their influence on the position of the CM at the block clearing.

At the block clearing, a greater VCM for elite sprinters (3.48 ± 0.05 m·s^{-1} for elite and 3.24 ± 0.18 m·s^{-1} for well-trained sprinters) conforms to the results of other studies, which demonstrate that the horizontal velocity of the CM at the block clearing of highly skilled participants (10.02–10.79 s/100 m time) ranged from 3.46 to 4.11 m·s^{-1}. Less-skilled sprinters (11.5–11.85 s/100 m time) have displayed lower block velocities of 2.94 to 2.95 m·s^{-1} (9,18). Thus, the ability of a sprinter to leave the blocks at a high velocity increases with his sprint performance over 100 m (18). Equation 1 (see Methods) suggests that a greater impulse explains this ability to leave the blocks at a high velocity.

Indeed, during the pushing phase, the impulse is greater in the elite sprinters (276.2 ± 36.0 N·s for elite and 215.4 ± 28.5 N·s^{-1} for well-trained sprinters). In accordance with classic mechanical physics, the impulse of a movement is defined as the area under the force-time curve. The size of this area depends on 3 main parameters: the duration of force application, the RFD, and the maximal force reached. No difference in the duration of force application has been found between elite and well-trained sprinters. Indeed, the time block was not significantly different between elite and well-trained sprinters (Table 4). The RFD was greater in elite sprinters (Table 4). The RFD exerted within the early phase of rising muscle force can be defined as the rate of rise in contractile force at the onset of contraction and is generally called "explosive muscle strength" (17,29,30). During fast limb movements, the short contraction time may not allow maximal muscle force to be reached. As a result, any increase in contractile RFD becomes highly significant because it allows a higher level of muscle force to be reached in the early phase of muscle contraction (e.g., within the initial 0.100–0.200 s of contraction). During the pushing phase on the starting block, the maximal acceleration (A_{peak1}) was reached when the rear foot pushed on the rear block and in a very short time, less than 0.150 seconds. Thus, RFD was an extremely important parameter in the ability to leave the blocks at a high velocity. In addition to RFD, another important muscular strength parameter is the maximal force that can be produced within a given contraction time. This maximal force produced during the pushing phase is the product between the body mass and the maximal acceleration of the CM of the body (e.g., Newton's second law of motion). The maximal acceleration reached during the pushing phase (A_{peak1}) was not significantly different between elite and well-trained sprinters. Only the body mass was higher in elite sprinters. Thus, the difference in impulse between elite and well-trained sprinters was directly associated with body mass and RFD.

These differences in RFD and body mass between the elite and the well-trained sprinters could be explained by the level of resistance training. Indeed, resistance training induces an increase in explosive muscle strength associated with neural adaptations (1) and muscle hypertrophy (21). The elite sprinter population used in this study have carried out much more resistance training than well-trained sprinters. Indeed, the elite sprinters completed a resistance training session 3 times a week, and they presented very high strength capacities (they were able to squat approximately 2.5–3 times their body weight for a half squat). Thus, the improvement of strength capacity in sprinters could be a key factor for improving VCM during the block phase (28).

However, differences between the elite and well-trained sprinters are not only a result of differences in strength, muscle mass, or resistance training. Indeed, other factors such as experience, technique, or innate capacity may be involved in these differences.

At the landing of the first step, elite sprinters had a greater XCM_{land} than well-trained sprinters. The greater velocity at the clearing block and the greater SL between the rear foot in the block and the first step explain this result. At the toe-off of the first step, XCM_{to} was also greater in elite sprinters (Figure 5). At the landing of the second step, elite sprinters did not have a greater XCM_{land}. Compared with the landing of the first step, the difference in XCM_{land} between elite and well-trained was reduced (18% to 7%) (Tables 6 and 7). This result is surprising because VCM_{to} and V_{mean} during the contact of the first step were greater in elite sprinters. Both parameters allow projection of the CM further forward than as was so in the well-trained sprinters. The fact that XCM_{land} was not greater in elite runners could be explained by the bad coordination of elite sprinters during the flight phase that follows the first step.

As shown in Figure 6, the elite sprinters presented a greater VCM at the toe-off of the first and the second steps. The greater impulse in the elite sprinters during both steps explains this result. Here, the greater impulse in the elite sprinters is associated only with their greater body mass and not with the RFD as was the case in the block phase. They also had a lower $VYCM_{to}$, which improves the orientation of the vector speed compared with the well-trained sprinters.

To conclude, the present study shows that, to start faster, elite sprinters placed their CM as close as possible to the finish line (Figure 5). It appears that their greater "explosive muscle strength" and better arm coordination allowed them to have a greater RFD and impulse and thus a greater velocity of their CM from the block phase until the toe-off of the second step (Figure 6).

Practical Applications

The present results demonstrate that coordination and strength capacity are key factors to improve the efficiency of the starting block phase and subsequent acceleration phase. Coordination and strength capacity can be improved considerably with resistance training (10).

From a practical point of view, a resistance training program aimed at inducing morphologic and neural changes in sprinters will always constitute a mixture of different methods. These methods are related to one another in a hierarchical way. First, power training is performed. This power training is characterised by a large number of sets of repetitions with submaximal loads of 60–80%, where 100% is the maximum weight that can be handled in a dynamic situation. The execution of the movement is performed at maximal velocity. The exercise stops when the velocity of the movement decreases. Second, resistance training must be performed with power training. Methods to improve strength use a small number of sets of repetitions with maximal loads of 80–100% (or, in the case of eccentric actions, supramaximal loads). In these exercises, the movement velocity of the load is relatively low, but the neuromuscular action is maximal. As in sprinting, high-velocity contraction is of major importance. Therefore, power and strength training must be followed by speed training. Third, speed training methods demand loads that the athlete can displace with a high velocity of movement execution. These loads are lower than 60% of the maximal load. Delecluse (10) suggested that, to reduce the deceleration induced by the stop of the load at the end of an explosive concentric movement, these movements can be replaced by ballistic movements including stretch-shortening cycle, bench throwing, or squat jumping.

To establish a transfer between resistance training and fast running, there is still a need for specific sprint exercises that include a strength component. Two groups of methods have been developed: overspeed and overload running (10). To improve the efficiency of the block phase and the subsequent acceleration, overload running is suggested. The classic overload training technique is incline running. Indeed, there is a mechanical similarity between the starting block phase and subsequent acceleration and incline running. Incline running induces an increase of the push-off time that is also observed during the acceleration phase of a sprint. Incline sprint running (with slope greater than 3%) could be beneficial to performance as related to the specific acceleration phase (27).

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