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Abstract

This study aimed to measure the contribution of each body segment to the production of total body kinetic energy during a 40-m sprint. Nine **recreational** sprinters performed two 40-m sprints wearing a MVN Biomech suit (Xsens). Data recorded were used to calculate total body kinetic energy (KE), and the KE of each segment. The KE of each segment was then expressed as a percentage of the total body KE. We divided the sprint into 3 phases: 1-start to maximal power (P_{max}), 2-P_{max} to maximal velocity (V_{max}), and 3-V_{max} to the end of the 40m. Total body KE increased from the start to the end of the 40-m sprint (from 331.3 ± 68.4 J in phase 1 to 2378.8 ± 233.0 J in phase 3 $p \leq 0.001$). The contribution of the head-trunk increased (from 39.5 ± 2.4% to 46.3 ± 1.1% $p \leq 0.05$). Contribution of the upper and lower limbs decreased over the 3 phases (respectively from 15.7 ± 2.5% to 10.6 ± 0.6% and from 44.8 ± 2.1% to 43.1 ± 1.5%; $p \leq 0.05$). This study revealed the important contribution of the trunk to forward propulsion throughout the entire acceleration phase.

Keywords: Inertial sensors, sprint performance, kinetic energy, power, performance

Introduction

Sprint performance is determined by the ability of the sprinter to generate high velocity (V_0), high power (P_{max}) **and** forces (F_0) at the centre of mass (CoM). Performance can thus be characterised by the force-velocity (*F-v*) and power-velocity (*P-v*) profiles of the sprinter's CoM (Morin et al., 2012; Rabita et al., 2015; Slawinski et al., 2017b). The mean power (P_{mean}) produced during a 40m sprint has also been shown to be closely related to sprint performance time (Rabita et al., 2015).

In physics, power is the rate, with respect to time, at which work is done; thus power is the time derivative of work. As such, several studies have evaluated external work (W_{ext}), defined as the sum of the potential and kinetic energy variations measured at the centre of mass level, in order to identify the overall mechanical determinants of sprinting. A recent study of twelve young, male athletes performing a maximal 60m sprint (Matsuo et al., 2019) showed that performance mainly depended on horizontal anterior–posterior W_{ext} during the propulsion phase. In other words, the greater the mechanical work produced, the higher the sprint performance. Indeed, the use of the kinetic energy (KE) of the body segments, because it take into account mass and velocity of each segment, supplies useful information concerning the upper and lower limbs' contributions to the translation of the body in the forward direction during rapid movement (Hubley and Wells, 1983; J Slawinski et al., 2010).

Internal mechanical work (W_{int}) is an important component of total work production during sprinting (Winter, 2009) and analysis of this variable provides important information to understand overall performance. In the literature, two methods have been used to calculate W_{int} during sprinting. The first method involves calculation of the power produced at each lower limb joint (ankle, knee and hip) and its contribution to the total power produced (sum of the power at each joint). This method has been used at discrete instants of the acceleration phase: during the starting block phase (Bezodis et al., 2015; Brazil et al., 2016; Mero et al., 2006; Otsuka et al., 2015), during the first step (Brazil et al., 2016; Charalambous et al., 2012; Debaere, 2012; 2013; Mero et al., 2006), during the second step (Debaere et al., 2012; Debaere et al., 2013; Jacobs and van Ingen Schenau, 1992), at 14-m (Johnson & Buckley, 2001) and at maximal velocity (V_{max}) (Belli et al., 2002; Bezodis et al., 2008; Vardaxis & Hoshizaki, 1989). However, the data from these studies do not show how lower limbs joint powers or the contribution of each joint, evolve throughout the course of the acceleration (table 1). More recently, Schache et al. (2019) calculated lower limb joint powers during the entire acceleration phase using data from a combination of 8 force plates integrated within the track and 22 Vicon 3D motion analysis cameras. They demonstrated that positive power produced at the hip, knee and ankle joints decreased as running speed increased, and that the contribution of the ankle joint to the total power produced by the lower limb increased with increasing CoM velocity. The authors concluded that the hip, and in particular the ankle joints, provided key sources of positive power that contributed to maximising the body's forward kinetic energy during a rapid acceleration. Despite some disparities, overall, these studies suggest that ankle joint power might play an important role in the production of mean power over the sprint (P_{mean}) since the contribution of ankle joint power to total power increases until V_{max}. In contrast, the contribution of hip joint power is greater during the start and the acceleration phase while the contribution of the knee is stable throughout the acceleration phase. Although these studies provided important information to increase understanding of performance, they did not consider the trunk and upper limbs which play an important role in sprinting (Slawinski et al., 2010; Slawinski et al., 2012, 2017a).

The second method involves calculation of W_{int} or internal power (P_{int}) using total body kinetic energy (KE). Recently, using this method, it was demonstrated that P_{int} accounts for 41% of the total power measured during a 20m sprint acceleration (Pavei et al., 2019). In order to understand the role of each segment (and particularly the upper limbs) in the production of P_{int}, a series of papers measured the KE of each segments during the starting block phase and first step (Slawinski et al., 2010; Slawinski et al., 2012, 2017a). These authors found that the trunk contributed 41% of the kinetic energy, the arms and forearms around 17% and the lower limbs about 42%. These data suggested that the upper limbs and particularly the trunk play a central role in the production of the total body KE, however, only the starting block phase and first step has been analysed the entire acceleration phase remains to be explore.

The aim of this study was therefore to calculate the KE of each limb segment and the contribution of each to total body kinetic energy throughout the entire acceleration phase of a 40m sprint. We hypothesised that the contribution of the lower limb segments and trunk would increase during the acceleration phase and in consequence, the contribution of the upper limbs would decrease.

Material and Methods

Subjects and experimental procedure

Nine athletes who were not specifically sprinters (mean height 181.6 ± 6.8 cm; mean mass 70.3 ± 9.2 kg; mean age 19.5 ± 1.1 years) performed two maximal 40-m sprints: this distance was chosen to ensure that the entire acceleration phase could be recorded (Morin et al., 2015). Each sprint was performed from a stand-up start and a five-minute recovery period was imposed between the two sprints. All participants provided informed consent for their participation. The protocol was in accordance with the ethical standards of the Declaration of Helsinki and the study was approved by the Institutional National Science in Sport Review Board.

During the sprints, participants wore a MVN Biomech suit (Xsens Technologies BV, Enschede, The Netherlands) onto which 17 miniature inertial measurement units were strapped (nanotechnology inertial measurement units, nIMU). Each nIMU contains three gyroscopes, three accelerometers and three magnetometers in a 35-g box about the size of a matchbox. This system was validated in running (Reenalda et al., 2016) and for high speed movement (Blair et al., 2018). Each nIMU captures the 6-degrees-of-freedom of the segment on which it is fixed, in real time at a sampling frequency of 240 Hz. Sensors were placed following the manufacturers recommendations; feet (dorsum), shanks (medial surface of the tibias), thighs (lateral surface, above the knees), pelvis (middle of both the posterior superior iliac spines), shoulders (middle of the scapula spine), upper arms (lateral, above the elbow), forearms (lateral side of wrist), hands (dorsum), sternum and the back of the head. A static (N-pose) and dynamic calibration was carried out for each participant. Sensor to segment orientations were then determined using regression equations (Blair et al., 2018; Roetenberg et al., 2013). Care was taken to ensure there were no materials that could provoke magnetic disturbances in the testing environment.

Data analysis

The raw data from the sensors (positions at each time-point) were exported to a customized MatLabTM program (7.10.0, R2010a, Natick, USA). This program was used to calculate the orientations of hands, fore-arms, upper-arms, head, upper-trunk, lower-trunk, pelvis, upper legs, lower legs and feet, wrist, elbow, shoulder, trunk, head, pelvis, hip, knee, ankle and metatarsus joint angles using a Newton-Euler method, and center of mass (CoM) positions and velocities of the body center of mass (CoM). The joints rotations sequences answer to the standard of the International Society of Biomechanics (Wu et al., 2005, 2002). Sixteen rigid segments (head–neck, thorax, abdomen, pelvis, upper arms, forearms, hands, thighs, legs and feet) were defined, and the kinetic energy (KE) during the entire acceleration phase was calculated for each segment according to the De Leva anthropometrical model (de Leva, 1996). The KE was calculated as the sum of translational and rotational KE of each segment. All the KE datas were then filtered using a zero phase butterworth filter of fourth order and 12Hz cutting frequency. This choice was made according to the residual method (Winter, 2009).

In order to understand the evolution of the KE during the 40-m sprint, we chose to divide the sprint into three different phases based on the maximal power (P_{max}) and maximal velocity of the CoM (V_{max}). Acceleration occurred during the first two phases while during the third phase, CoM velocity was stable. Phase 1 corresponded to the first movement made by the sprinter (determined by an increase in CoM velocity of 0.1 m.s^{-1}) to reach P_{max}, Phase 2 was began at P_{max} until V_{max} and phase 3 began at V_{max} until the end of the 40 m. We used the method proposed by Samozino to compute P_{max} and the time at which it was reached (Morin et al., 2019; Samozino et al., 2016). This simple method uses an mono-exponential model to describe the increase in velocity during the acceleration phase (di Prampero et al., 2005) (figure 1). Using this method, we also computed linear force – velocity (F–v) and second-order polynomial power – velocity (P–v) relationships for each participant in order to obtain maximal theoretical force, velocity and power values (respectively, F_0, V_0 and P_{max}) (figure 2 A and B). F_0 and V_0 are the respective intercepts of the force and velocity axes of the F–v curve. P_{max} is the maximum of the P–v relationship. Once V_{max} and P_{max} had been determined, the start and end-points of each of the 3 phases were defined according to the timing of these two variables.

Using a method previously published by our team, we calculated mean KE (KE_{mean}) for each phase and each segment (Slawinski et al., 2017a). The KE_{mean} of each segment was then summed to obtain whole body KE_{mean}, uppers limbs KE_{mean} (sum of left and right upper arms, forearms and hands KE_{mean}), **lowers limbs** KE_{mean} (sum of left and right thigh, lowers legs and feet KE_{mean}) and head–trunk limb KE_{mean} (sum of head–neck, thorax, abdomen, pelvis KE_{mean}) for the 3 sprint phases. KE_{mean} of each segment was expressed as a percentage of whole body KE_{mean} to determine the contribution of each segment to the forward velocity of the CoM during the whole sprint.

Statistical analysis

The KE_{mean} of the different segments and their contributions to total body KE were compared across the three phases using a repeated measures ANOVA, and a Bonferroni post-hoc test was used to compare the results for each phase. The level of significance was set at $p \leq 0.05$.

Results

F-v and P-v relationships

Mean V_0 for all participants was 8.47 ± 0.50 m.s^{-1}, mean F_0 was 462 ± 86 N and mean P_{max} was 971 ± 129 W.

The durations of phase 1 (start to P_{max}), phase 2 (P_{max} to V_{max}) and phase 3 (V_{max} to 40-m), were respectively 0.90 ± 0.17 s, 4.02 ± 0.89 s and 0.93 ± 0.77 s.

Mean kinetic energy

KE_{mean} of the total body increased significantly ($p \leq 0.001$) from phase 1 to phase 2 and from phase 2 to phase 3. Simirlarly, KE_{mean} of the head, neck, trunk, right and left upper arms and thigh segments increased significantly ($p \leq 0.001$) from phase 1 to phase 2 and from phase 2 to phase 3. The KE_{mean} of the other distal segments (right and left forearms, hands, legs and feet) only increased from phase 1 to phase 2 (figure 3 A, B, C, D).

Segmental contribution

The post-hoc test demonstrated that the contribution of the head–trunk limb to the forward velocity of the CoM increased significantly between phases 1 and 2 and between phases 1 and 3 ($p \leq 0.05$; table 2), but not between phases 2 and 3 (table 2). Inversely, the contribution of the upper and lower limbs to the forward velocity of the CoM decreased significantly from phase 1 to phase 2 and from phase 1 to phase 3 ($p \leq 0.05$; table 2), but not from phase 2 to phase 3 (table 2). Details of the contributions of the different segments are presented in table 2.

Discussion and implication

In this study, we calculated the KE of each body segment and the contribution of the main limbs to the production of total body KE during the entire acceleration phase of a 40m sprint. This was the first time that kinetic energy of all the segment has been measured during a 40 m run. This was possible though the use of an inertial measurement system allowing to continuously measure the body kinematics in ecological conditions. This approach allows to understand how maximal power, that has been identified as a strong sprint performance predictor, is produced by the different limbs (di Prampero et al., 2021). The present results demonstrated that KE_{mean} of the total body increased until the phase 3. This increase is explained by the increase in KE_{mean} of head-trunk-limb and the proximal limb segments (arms and thigh). KE_{mean} of distal segments (fore arms, hands, legs and feet) did not **contribute** to the increase in KE_{mean} of the total body when the sprinter has reached is V_{max} (between phase 2 and 3). The results also confirmed that, **during the entire sprint,** the head-trunk-limb and upper limbs together contributed more than 50% of total body KE. This contribution of the head-trunk-limb increased between the phase 1 and 2 demonstrating that the head-trunk-limb plays a central role in the velocity production during the acceleration phase.

F-v and P-v relationships

The present results highlight that, **thanks to the use** P_{max} and V_{max}, a sprint running race can be carved in three main phases. This approach allow to analyze the sprint through measurable mechanical parameters and not only with the classical phases obtained from technical observation (block clearance, driving phase, acceleration phase, top speed and maintenance or decrease)(Mann and Murphy, 2018). The present data obtained with Xsens match with those obtained for a fifth division soccer players who have a close V_{max} (Jimenez-reyes and Cuadrado, 2019). Indeed for a V_{max} of 8.7 $m.s^{-1}$ these authors found a F_0 of 6.7 $N.kg^{-1}$ and a P_{max} of 14.5 $W.kg^{-1}$ and in the present work, for a V_{max} of 8.47 $m.s^{-1}$, F_0 was 6.6 $N.kg^{-1}$ and a P_{max} was 13.9 $W.kg^{-1}$.

Mean kinetic energy and Segmental contribution

The first important result was that total body KE increased from the start to the end of the 40-m sprint. This increase was mathematically associated with the increase in trunk KE and the KE of the upper arms and thighs, which attach directly to the trunk (figure 3). This is not surprising given that the trunk, upper arms and thighs collectively represent more than 60% of total body mass. Thus, the hip and shoulder joints played a key role throughout the entire sprint. This supports the results of recent studies that have demonstrated the importance of hip muscle activity for sprint performance. For example, the muscles group of quadratus femoris, hamstring and gluteus are significantly larger in sprinters than in non-sprinters (Handsfield et al., 2017). Also, the mean power output developed during resistance exercise to develop hamstring strength, such as the hip thrust, is directly correlated to performance on 10, 20, 40 and 60-m sprints (Loturco et al., 2018). The hamstring muscles are strongly active in late swing, just before ground contact (Morin et al., 2015; Schache et al., 2012). Their role at this time point is two-fold: 1) to brake the leg at the end of the swing phase and 2) to increase thigh velocity to prepare for foot contact (Morin et al., 2013). We believe that the strong contribution of the trunk and thighs to forward motion of the CoM observed in this study throughout the sprint acceleration reflects the specific role of the hip muscles in sprint performance. To go deeper into the analysis of the role of the hip, we plotted typical continuous KE of upper, lower limb and head-trunk limb expressed as a percentage of the total energy (figure 4). This figure showed that lower limb and the head-trunk limb are in opposite phase, and suggested that trunk and legs make an opening and a closing movement during the sprint. This closing-opening movement is particularly important (great amplitude) during the phase 1 of the sprint. This suggested that this movement is a mechanism allowing to produce a great KE energy variation and to reach a higher P_{max} at the end of the phase 1. The efficiency of this closing-opening movement may particularly depend on the action of the hip muscles. The KE of the upper limb being also in opposite phase with the one of the head-trunk limb, we can hypothesise that upper and head-trunk limbs also make an opening-closing movement. This movement, as for lower limb, may help to create a greatest P_{max}. Thus, the sprinter would realise a double closing-opening movement between lower and head-trunk limb and between head-trunk and upper limb that increase P_{max} at the end of the phase 1.

The second important result was that, as hypothesised, the contribution of the upper limbs to total body KE decreased as sprint velocity increased. In a previous study, it has been showed that the upper limbs contribute 15 to 22% of the total body KE during the starting block phase and first step; the exact contribution depends on the training level of the sprinters and on their position during the start phase (Slawinski et al., 2010; Slawinski et al., 2017a). The present results confirmed this level of contribution (16%) of the upper limbs during the start of the acceleration (phase 1) and revealed that their contribution decreased significantly (to 11%) at maximal velocity (phase 3) (table 2). Compare to previous study the lower contribution of upper limb observed in the present study may be linked to the lower training status in sprint running of the participants. This decrease of the upper limb contribution during the 40m sprint is not surprising since the upper limb mass is much smaller than that of the trunk or lower limbs, thus, as sprint velocity increases, the relative contribution of the upper limbs must decrease. This was corroborated by the increase in the contribution of trunk and the head-neck segment (57.8% of the total body mass (Winter, 2009)) with increasing sprint velocity.

The third important result was that, in contrast with our hypothesis, the contribution of the lower limbs reduced over the course of the acceleration. This could be explained by the fact the lower limbs represent a smaller proportion of total body mass (32.3%) than the trunk and head-neck segments (Winter, 2009), and that small variations in legs velocity occurred between phases 1 and 3. In contrast to CoM velocity, step rate does not increase gradually throughout the acceleration phase: the rate of the first step after leaving the starting block is already at 95% of the rate reached at V_{max} (Debaere et al., 2013). Thus lower limb velocity remains relatively constant from the sprint start until V_{max}. The reduction in the relative contribution of the lower limbs to forward motion of the body CoM seemed to compensate for the increase in trunk contribution from phase 1 to phase 2 (in phase 2, the contribution of the trunk was greater than that of the lower limb, in contrast with phase 1; table 2). However, the decrease in the lower limb contribution at V_{max} is surprising, particularly in the light of the recent results of Schache et al. (2019) that showed that ankle power increased at V_{max}. This difference could be explained firstly by the fact that we evaluated lower limb segmental energy, which is mechanically different to joint power which was evaluated by Schache et al. (2019); and secondly, the role of the trunk, thigh and thus hip joint could be to create sagital movement, while the role of the ankle joint appears to be to create large vertical reaction forces at V_{max} (Weyand et al., 2000).

Conclusion

The results of this study revealed that, as well as the lower limbs, the upper limbs, and particularly the trunk, contribute to total body KE during sprint acceleration. Trunk KE contributed largely to total body KE throughout the entire acceleration, while the contribution of the upper and lower limbs reduced over the course of the sprint. Others studies must be conducted in sprinters with a better maximal velocity and maximal power in order to confirm if movement of closing-opening between legs, trunk and arms are determinant in the production of a hight kinetic energy and a maximal power. If this was confirmed, the start phase and first step would no longer be considered as a simple pushing phase but as a succession of a closing and opening movement, where the trunk, hip and shoulders would play a central role.

Declaration of interest statement

All authors disclose any financial and personal relationships with other people or organisations that could inappropriately influence (bias) their work.

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Tables

	Rear block	Front block	First step	Second step	14-m	V_{max}
Hip (W)	1068 ± 257	1426 ± 247	1648 ± 314	1648 ± 314	2100	2120 ± 170
Knee (W)	126 ± 34	878 ± 373	828 ± 312	828 ± 312	1000	1250 ± 354
Ankle (W)	556 ± 62	971 ± 797	1652 ± 543	1652 ± 543	2900	2800 ± 283

Table 1: Maximal hip, knee and ankle joint power (mean ± SD) according to the distance of the sprint acceleration (rear and front block refer to the starting block phase). All the values were established from data found in the literature (see text for references).

	Phase 1 (% of total body KE_{mean})	**Phase 2 (% of total body KE_{mean})**	**Phase 3 (% of total body KE_{mean})**
Head-Neck	5.6 ± 0.4	6.3 ± 0.2*	6.2 ± 0.5*
Trunck	12.5 ± 0.8	14.5 ± 0.3*	14.5 ± 0.5*
Abdomen	12.3 ± 1.2	14.5 ± 0.8*	14.8 ± 0.7*
Pelvis	9.2 ± 0.4	10.6 ± 0.5*	10.8 ± 0.7*
Sum of Head–trunck-limb	*39.5 ± 2.4*	*45.9 ± 0.8**	*46.3 ± 1.1**
Right Thigh	14.4 ± 1.7	14.1 ± 0.4	14.9 ± 2.5
Right Leg	6.4 ± 1.3	5.3 ± 0.4	5.5 ± 2.0
Right Foot	2.3 ± 0.6	2.1 ± 0.1	2.1 ± 0.8
Left Thigh	13.7 ± 1.2	14.0 ± 0.3	14.1 ± 2.1
Left Leg	5.8 ± 1.2	5.3 ± 0.3	4.8 ± 1.8
Left Foot	2.2 ± 0.5	2.1 ± 0.1	1.8 ± 0.7
Sum of lower Limb	*44.8 ± 2.1*	*42.9 ± 1.3**	*43.1 ± 1.5**
Right Arm	2.9 ± 0.3	2.7 ± 0.1	2.6 ± 0.4
Right Forearm	2.8 ± 0.7	1.9 ± 0.2*	1.7 ± 0.5*
Right Hand	2.0 ± 0.7	1.0 ± 0.1*	0.8 ± 0.2*
Left Arm	2.8 ± 0.3	2.7 ± 0.1	2.7 ± 0.4
Left Forearm	2.9 ± 0.4	1.9 ± 0.2*	1.8 ± 0.4*
Left Hand	2.2 ± 0.5	1.0 ± 0.1*	0.9 ± 0.2*
Sum of upper Limb	*15.7 ± 2.5*	*11.2 ± 0.8**	*10.6 ± 0.6**

Table 2: Contribution of the different segments to the total body kinetic energy for the 3 phases of the 40-m sprint. *Significantly different from phase 1 ($p \leq 0.05$).

Figures

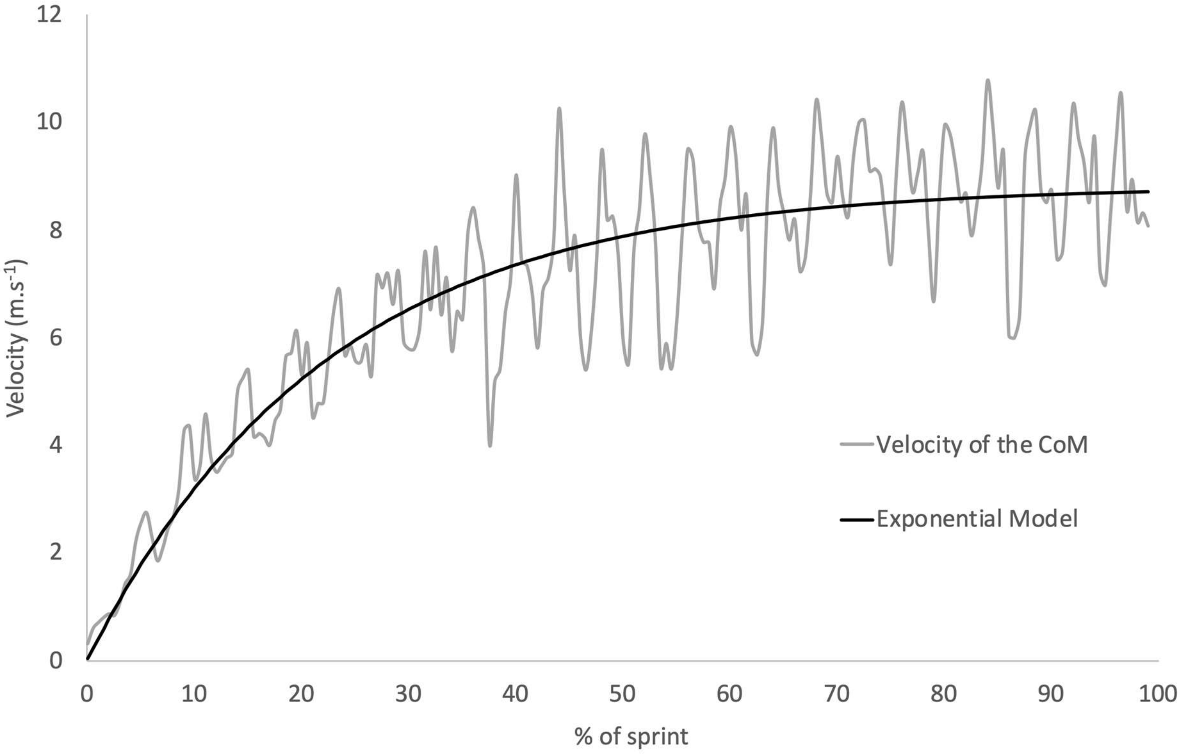

Figure 1: Exponential model applied to the increase of the typical non-fitted velocity of the CoM during the 40-m sprint.

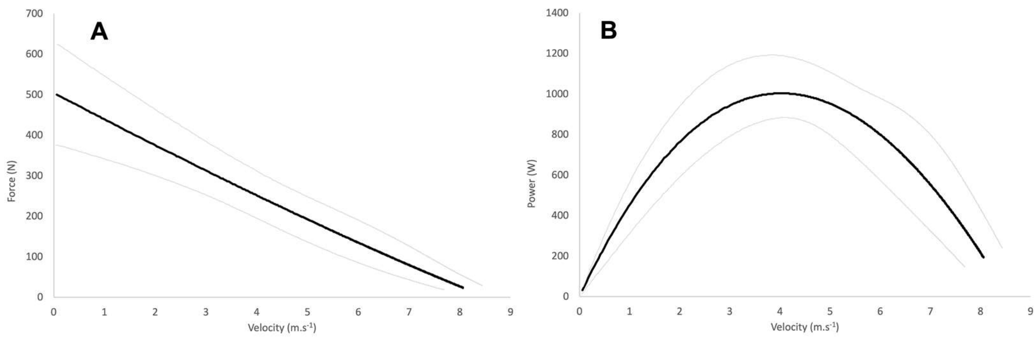

Figure 2: Average force-velocity (A) and power-velocity (B) relationships derived from the exponential model of the increase in CoM velocity during the acceleration phases.

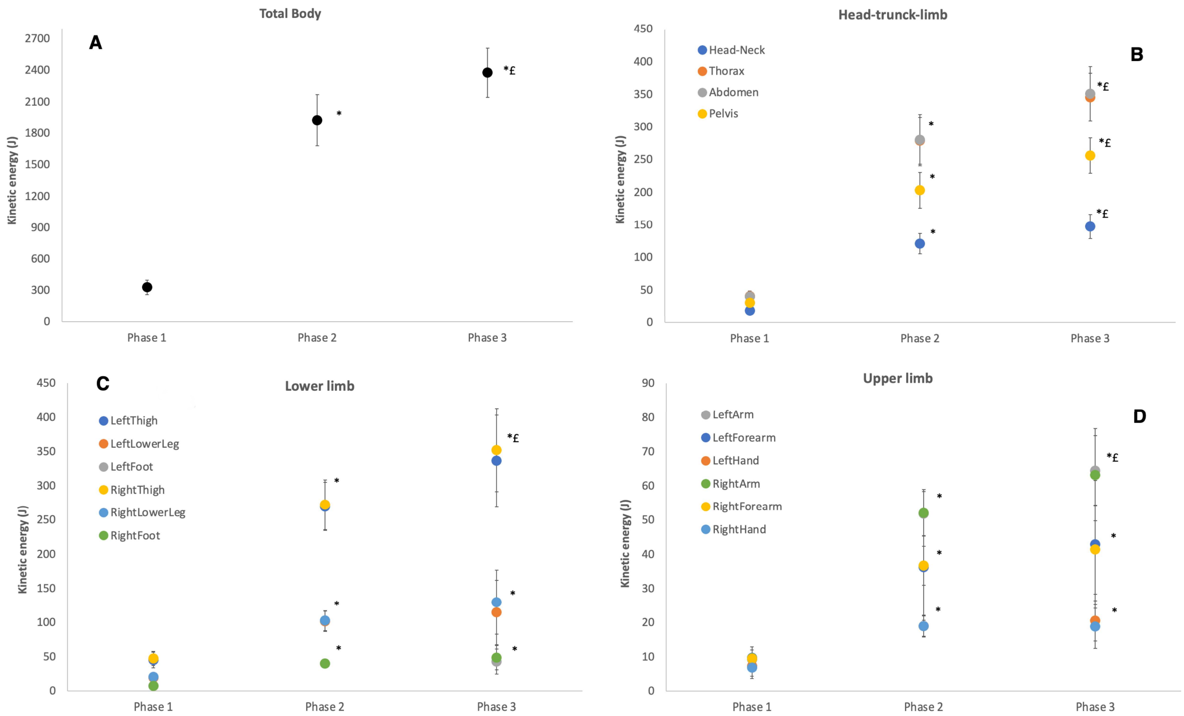

Figure 3: Total body kinetic energy (A) and kinetic energy of the 16 body segments. Mean kinetic energy was calculated for the 3 phases of the 40-m sprint (Start to P_{max}; P_{max} to V_{max} and V_{max} to the end of the sprint). The KE_{mean} of each segment was summed for each limb. Head-trunk-limb (B) is composed of the head-neck, thorax, abdomen and pelvis; lower limb (C) is composed of the right and left thighs, legs and feet; and upper limb (D) is composed of the right and left upper arms, forearms and hands. *Significantly different from phase 1 ($p \leq 0.05$); £Significantly different from phase 2 ($p \leq 0.05$).

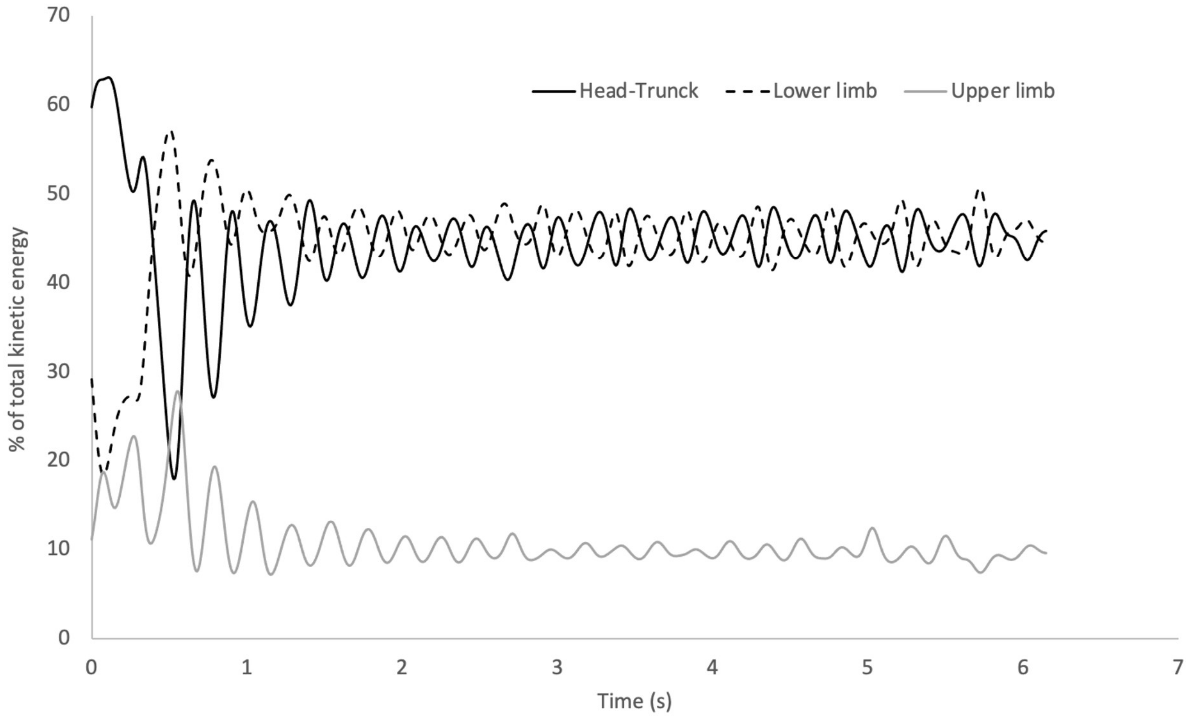

Figure 4: Typical example of continuous plotting of the lower limb, Head-trunck and lower limb expressed as a percentage of total kinetic energy.