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1 **Contribution of segmental kinetic energy to forward propulsion of the centre of mass:**
2 **analysis of sprint acceleration**

3 **Jean Slawinski ^{1*}, Nicolas Houel ³, Camille Moreau², Alexia Mahlig^{1,4} and Daniel Dinu ¹**

4 ¹ French National Institute of Sport, Expertise and Performance. Sport, Expertise and Performance Lab, EA7370, Paris,
5 France; daniel.dinu@insep.fr; Alexia.Mahlig@USherbrooke.ca; jean.slawinski@insep.fr

6 ² University of Paris Nanterre UFRSTAPS, LINP-2APS - Laboratoire Interdisciplinaire en Neurosciences, Physiologie et
7 Psychologie : Activité Physique, Santé et Apprentissages, Nanterre, France. jslawinski@parisnanterre.fr;
8 moreau_camille@live.fr

9 ³ University of Reims, Champagne Ardennes UFRSTAPS, Laboratory of Performance, Santé, Métrologie, Société (EA-
10 7507), Reims, France. nicolas.houel@univ-reims.fr

11 ⁵ Université de Sherbrooke, Département de génie mécanique, Sherbrooke, QC, Can

12 * Correspondence: jean.slawinski@insep.fr ; Tel.: +33 1 41 74 41 23

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15 **Words count: 3457**

16 **Abstract**

17 This study aimed to measure the contribution of each body segment to the production of
18 total body kinetic energy during a 40-m sprint. Nine **recreational** sprinters performed two 40-
19 m sprints wearing a MVN Biomech suit (Xsens). Data recorded were used to calculate total
20 body kinetic energy (KE), and the KE of each segment. The KE of each segment was then
21 expressed as a percentage of the total body KE. We divided the sprint into 3 phases: 1-start to
22 maximal power (P_{\max}), 2- P_{\max} to maximal velocity (V_{\max}), and 3- V_{\max} to the end of the 40m.
23 Total body KE increased from the start to the end of the 40-m sprint (from 331.3 ± 68.4 J in
24 phase 1 to 2378.8 ± 233.0 J in phase 3 $p \leq 0.001$). The contribution of the head-trunk increased
25 (from $39.5 \pm 2.4\%$ to $46.3 \pm 1.1\%$ $p \leq 0.05$). Contribution of the upper and lower limbs
26 decreased over the 3 phases (respectively from $15.7 \pm 2.5\%$ to $10.6 \pm 0.6\%$ and from $44.8 \pm$
27 2.1% to $43.1 \pm 1.5\%$; $p \leq 0.05$). This study revealed the important contribution of the trunk to
28 forward propulsion throughout the entire acceleration phase.

29

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

31

32 **Introduction**

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

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

50 Internal mechanical work (W_{int}) is an important component of total work production
51 during sprinting (Winter, 2009) and analysis of this variable provides important information to
52 understand overall performance. In the literature, two methods have been used to calculate W_{int}
53 during sprinting. The first method involves calculation of the power produced at each lower
54 limb joint (ankle, knee and hip) and its contribution to the total power produced (sum of the
55 power at each joint). This method has been used at discrete instants of the acceleration phase:
56 during the starting block phase (Bezodis et al., 2015; Brazil et al., 2016; Mero et al., 2006;
57 Otsuka et al., 2015), during the first step (Brazil et al., 2016; Charalambous et al., 2012;
58 Debaere, 2012; 2013; Mero et al., 2006), during the second step (Debaere et al., 2012; Debaere
59 et al., 2013; Jacobs and van Ingen Schenau, 1992), at 14-m (Johnson & Buckley, 2001) and at
60 maximal velocity (V_{\max}) (Belli et al., 2002; Bezodis et al., 2008; Vardaxis & Hoshizaki, 1989).
61 However, the data from these studies do not show how lower limbs joint powers or the
62 contribution of each joint, evolve throughout the course of the acceleration (table 1). More

63 recently, Schache et al. (2019) calculated lower limb joint powers during the entire acceleration
64 phase using data from a combination of 8 force plates integrated within the track and 22 Vicon
65 3D motion analysis cameras. They demonstrated that positive power produced at the hip, knee
66 and ankle joints decreased as running speed increased, and that the contribution of the ankle
67 joint to the total power produced by the lower limb increased with increasing CoM velocity.
68 The authors concluded that the hip, and in particular the ankle joints, provided key sources of
69 positive power that contributed to maximising the body's forward kinetic energy during a rapid
70 acceleration. Despite some disparities, overall, these studies suggest that ankle joint power
71 might play an important role in the production of mean power over the sprint (P_{mean}) since the
72 contribution of ankle joint power to total power increases until V_{max} . In contrast, the
73 contribution of hip joint power is greater during the start and the acceleration phase while the
74 contribution of the knee is stable throughout the acceleration phase. Although these studies
75 provided important information to increase understanding of performance, they did not consider
76 the trunk and upper limbs which play an important role in sprinting (Slawinski et al., 2010;
77 Slawinski et al., 2012, 2017a).

78 The second method involves calculation of W_{int} or internal power (P_{int}) using total body
79 kinetic energy (KE). Recently, using this method, it was demonstrated that P_{int} accounts for
80 41% of the total power measured during a 20m sprint acceleration (Pavei et al., 2019). In order
81 to understand the role of each segment (and particularly the upper limbs) in the production of
82 P_{int} , a series of papers measured the KE of each segments during the starting block phase and
83 first step (Slawinski et al., 2010; Slawinski et al., 2012, 2017a). These authors found that the
84 trunk contributed 41% of the kinetic energy, the arms and forearms around 17% and the lower
85 limbs about 42%. These data suggested that the upper limbs and particularly the trunk play a
86 central role in the production of the total body KE, however, only the starting block phase and
87 first step has been analysed the entire acceleration phase remains to be explore.

88 The aim of this study was therefore to calculate the KE of each limb segment and the
89 contribution of each to total body kinetic energy throughout the entire acceleration phase of a
90 40m sprint. We hypothesised that the contribution of the lower limb segments and trunk would
91 increase during the acceleration phase and in consequence, the contribution of the upper limbs
92 would decrease.

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95

96 **Material and Methods**

97

98 *Subjects and experimental procedure*

99 Nine athletes who were not specifically sprinters (mean height 181.6 ± 6.8 cm; mean
100 mass 70.3 ± 9.2 kg; mean age 19.5 ± 1.1 years) performed two maximal 40-m sprints: this
101 distance was chosen to ensure that the entire acceleration phase could be recorded (Morin et al.,
102 2015). Each sprint was performed from a stand-up start and a five-minute recovery period was
103 imposed between the two sprints. All participants provided informed consent for their
104 participation. The protocol was in accordance with the ethical standards of the Declaration of
105 Helsinki and the study was approved by the Institutional National Science in Sport Review
106 Board.

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

122 *Data analysis*

123 The raw data from the sensors (positions at each time-point) were exported to a customized
124 MatLab™ program (7.10.0, R2010a, Natick, USA). This program was used to calculate the
125 orientations of hands, fore-arms, upper-arms, head, upper-trunk, lower-trunk, pelvis, upper
126 legs, lower legs and feet, wrist, elbow, shoulder, trunk, head, pelvis, hip, knee, ankle and
127 metatarsus joint angles using a Newton-Euler method, and center of mass (CoM) positions and
128 velocities of the body center of mass (CoM). The joints rotations sequences answer to the
129 standard of the International Society of Biomechanics (Wu et al., 2005, 2002). Sixteen rigid

130 segments (head–neck, thorax, abdomen, pelvis, upper arms, forearms, hands, thighs, legs and
131 feet) were defined, and the kinetic energy (KE) during the entire acceleration phase was
132 calculated for each segment according to the De Leva anthropometrical model (de Leva, 1996).
133 The KE was calculated as the sum of translational and rotational KE of each segment. All the
134 KE datas were then filtered using a zero phase butterworth filter of fourth order and 12Hz
135 cutting frequency. This choice was made according to the residual method (Winter, 2009).

136
137 In order to understand the evolution of the KE during the 40-m sprint, we chose to divide
138 the sprint into three different phases based on the maximal power (P_{\max}) and maximal velocity
139 of the CoM (V_{\max}). Acceleration occurred during the first two phases while during the third
140 phase, CoM velocity was stable. Phase 1 corresponded to the first movement made by the
141 sprinter (determined by an increase in CoM velocity of $0.1 \text{ m}\cdot\text{s}^{-1}$) to reach P_{\max} , Phase 2 was
142 began at P_{\max} until V_{\max} and phase 3 began at V_{\max} until the end of the 40 m. We used the
143 method proposed by Samozino to compute P_{\max} and the time at which it was reached (Morin et
144 al., 2019; Samozino et al., 2016). This simple method uses an mono-exponential model to
145 describe the increase in velocity during the acceleration phase (di Prampero et al., 2005) (figure
146 1). Using this method, we also computed linear force – velocity (F – v) and second-order
147 polynomial power – velocity (P – v) relationships for each participant in order to obtain maximal
148 theoretical force, velocity and power values (respectively, F_0 , V_0 and P_{\max}) (figure 2 A and B).
149 F_0 and V_0 are the respective intercepts of the force and velocity axes of the F – v curve. P_{\max} is
150 the maximum of the P – v relationship. Once V_{\max} and P_{\max} had been determined, the start and
151 end-points of each of the 3 phases were defined according to the timing of these two variables.

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

160 *Statistical analysis*

161 The KE_{mean} of the different segments and their contributions to total body KE were
162 compared across the three phases using a repeated measures ANOVA, and a Bonferroni post-

163 hoc test was used to compare the results for each phase. The level of significance was set at p
164 ≤ 0.05 .

165
166

167 **Results**

168 *F-v and P-v relationships*

169 Mean V_0 for all participants was $8.47 \pm 0.50 \text{ m}\cdot\text{s}^{-1}$, mean F_0 was $462 \pm 86 \text{ N}$ and mean
170 P_{max} was $971 \pm 129 \text{ W}$.

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

173

174 *Mean kinetic energy*

175 KE_{mean} of the total body increased significantly ($p \leq 0.001$) from phase 1 to phase 2 and
176 from phase 2 to phase 3. Similarly, KE_{mean} of the head, neck, trunk, right and left upper arms
177 and thigh segments increased significantly ($p \leq 0.001$) from phase 1 to phase 2 and from phase
178 2 to phase 3. The KE_{mean} of the other distal segments (right and left forearms, hands, legs and
179 feet) only increased from phase 1 to phase 2 (figure 3 A, B, C, D).

180 *Segmental contribution*

181 The post-hoc test demonstrated that the contribution of the head–trunk limb to the forward
182 velocity of the CoM increased significantly between phases 1 and 2 and between phases 1 and
183 3 ($p \leq 0.05$; table 2), but not between phases 2 and 3 (table 2). Inversely, the contribution of
184 the upper and lower limbs to the forward velocity of the CoM decreased significantly from
185 phase 1 to phase 2 and from phase 1 to phase 3 ($p \leq 0.05$; table 2), but not from phase 2 to
186 phase 3 (table 2). Details of the contributions of the different segments are presented in table 2.

187

188

189

190 **Discussion and implication**

191

192 In this study, we calculated the KE of each body segment and the contribution of the main
193 limbs to the production of total body KE during the entire acceleration phase of a 40m sprint.
194 This was the first time that kinetic energy of all the segment has been measured during a 40 m
195 run. This was possible though the use of an inertial measurement system allowing to
196 continuously measure the body kinematics in ecological conditions. This approach allows to

197 understand how maximal power, that has been identified as a strong sprint performance
198 predictor, is produced by the different limbs (di Prampero et al., 2021). The present results
199 demonstrated that KE_{mean} of the total body increased until the phase 3. This increase is explained
200 by the increase in KE_{mean} of head-trunk-limb and the proximal limb segments (arms and thigh).
201 KE_{mean} of distal segments (fore arms, hands, legs and feet) did not **contribute** to the increase
202 in KE_{mean} of the total body when the sprinter has reached is V_{max} (between phase 2 and 3). The
203 results also confirmed that, **during the entire sprint**, the head-trunk-limb and upper limbs
204 together contributed more than 50% of total body KE. This contribution of the head-trunk-limb
205 increased between the phase 1 and 2 demonstrating that the head-trunk-limb plays a central role
206 in the velocity production during the acceleration phase.

207 *F-v and P-v relationships*

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

217

218 *Mean kinetic energy and Segmental contribution*

219 The first important result was that total body KE increased from the start to the end of the
220 40-m sprint. This increase was mathematically associated with the increase in trunk KE and the
221 KE of the upper arms and thighs, which attach directly to the trunk (figure 3). This is not
222 surprising given that the trunk, upper arms and thighs collectively represent more than 60% of
223 total body mass. Thus, the hip and shoulder joints played a key role throughout the entire sprint.
224 This supports the results of recent studies that have demonstrated the importance of hip muscle
225 activity for sprint performance. For example, the muscles group of quadratus femoris,
226 hamstring and gluteus are significantly larger in sprinters than in non-sprinters (Handsfield et
227 al., 2017). Also, the mean power output developed during resistance exercise to develop
228 hamstring strength, such as the hip thrust, is directly correlated to performance on 10, 20, 40

229 and 60-m sprints (Loturco et al., 2018). The hamstring muscles are strongly active in late swing,
230 just before ground contact (Morin et al., 2015; Schache et al., 2012). Their role at this time
231 point is two-fold: 1) to brake the leg at the end of the swing phase and 2) to increase thigh
232 velocity to prepare for foot contact (Morin et al., 2013). We believe that the strong contribution
233 of the trunk and thighs to forward motion of the CoM observed in this study throughout the
234 sprint acceleration reflects the specific role of the hip muscles in sprint performance. To go
235 deeper into the analysis of the role of the hip, we plotted typical continuous KE of upper, lower
236 limb and head-trunk limb expressed as a percentage of the total energy (figure 4). This figure
237 showed that lower limb and the head-trunk limb are in opposite phase, and suggested that trunk
238 and legs make an opening and a closing movement during the sprint. This closing-opening
239 movement is particularly important (great amplitude) during the phase 1 of the sprint. This
240 suggested that this movement is a mechanism allowing to produce a great KE energy variation
241 and to reach a higher P_{\max} at the end of the phase 1. The efficiency of this closing-opening
242 movement may particularly depend on the action of the hip muscles. The KE of the upper limb
243 being also in opposite phase with the one of the head-trunk limb, we can hypothesise that upper
244 and head-trunk limbs also make an opening-closing movement. This movement, as for lower
245 limb, may help to create a greatest P_{\max} . Thus, the sprinter would realise a double closing-
246 opening movement between lower and head-trunk limb and between head-trunk and upper limb
247 that increase P_{\max} at the end of the phase 1.

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

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

279

280 **Conclusion**

281

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

291

292 **Declaration of interest statement**

293 All authors disclose any financial and personal relationships with other people or organisations
294 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*
Trunk	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*
<i>Sum of Head-trunk-limb</i>	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
<i>Sum of lower Limb</i>	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*
<i>Sum of upper Limb</i>	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

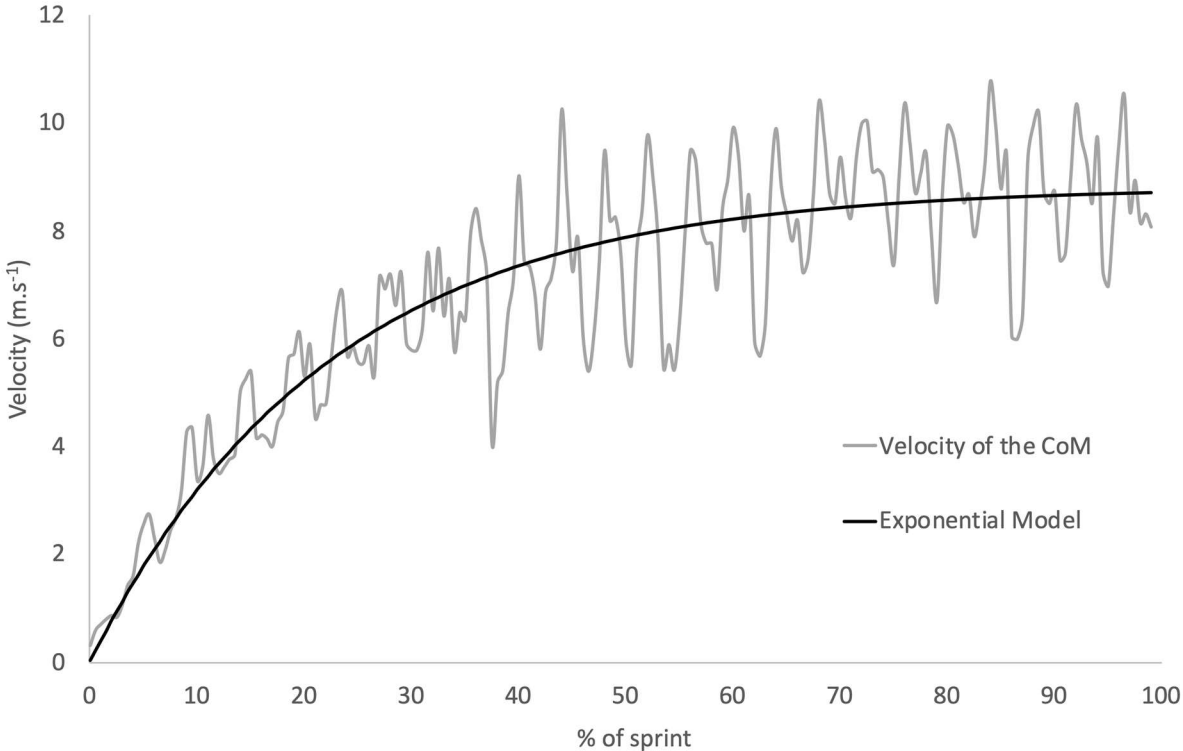


Figure 1: Exponential model applied to the increase of the typical non-fitted velocity of the CoM during the 40-m sprint.

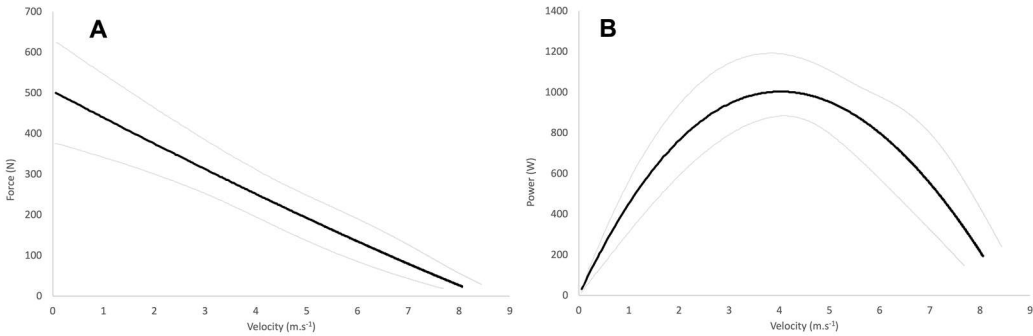


Figure 2: Average force-velocity (A) and power-velocity (B) relationships derived from the exponential model of the increase in CoM velocity during the acceleration phases.

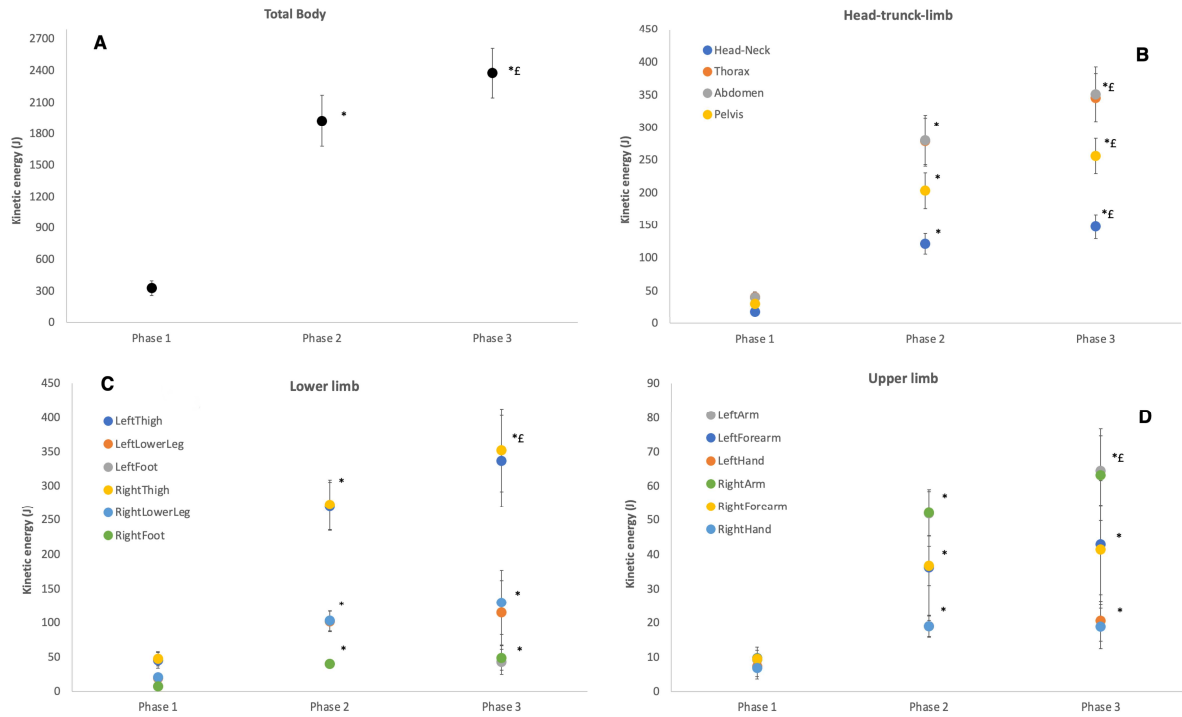


Figure 3: Total body kinetic energy (A) and kinetic energy of the 16 body segments. Mean kinetic energy was calculated for the 3 phases of the 40-m sprint (Start to P_{max} ; P_{max} to V_{max} and V_{max} to the end of the sprint). The KE_{mean} of each segment was summed for each limb. Head-trunk-limb (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 ($p \leq 0.05$).

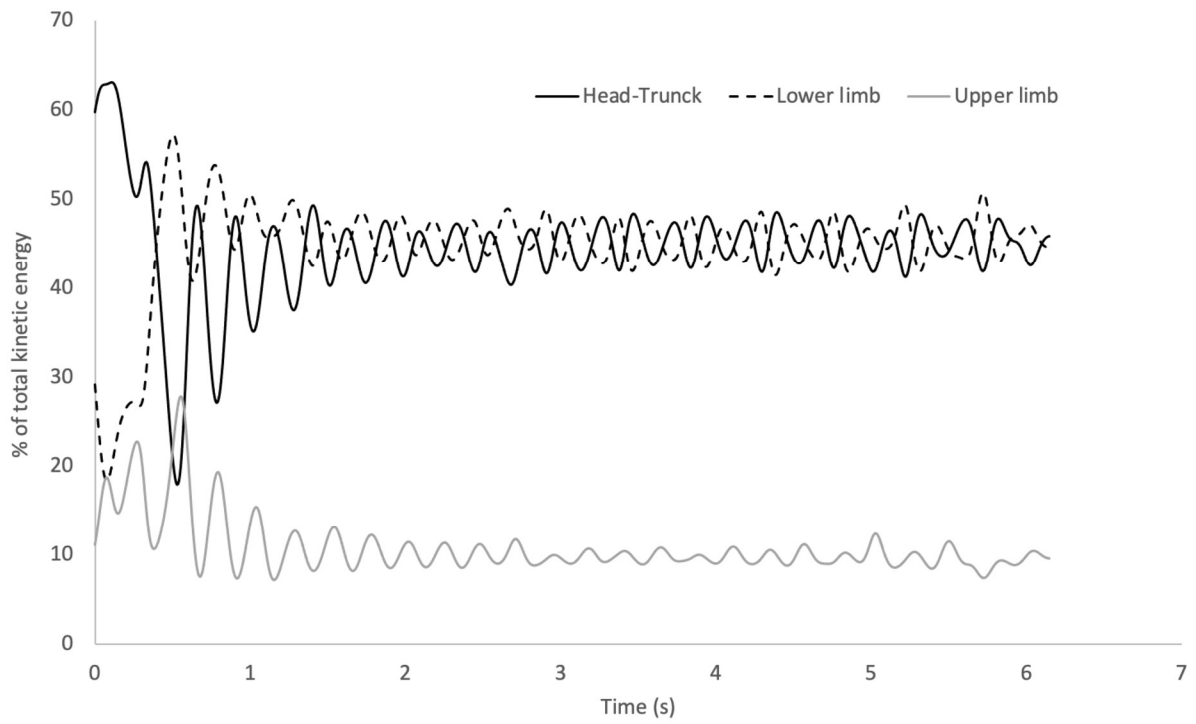


Figure 4: Typical example of continuous plotting of the lower limb, Head-trunk and lower limb expressed as a percentage of total kinetic energy.