ISSN 1750-9823 (print)
International Journal of Sports Science and Engineering
Vol. 03 (2009) No. 01, pp. 003-010

Assessment of the Influence of Pole Carriage on Sprint Kinematics: A Case Study of Novice Athletes

Julien Frere [1], Didier Chollet [1] and Claire Tourny-Chollet [1]

[1] CETAPS Laboratory UPRES EA 3832: University of Rouen, Faculty of Sports Sciences, France

(*Received January 20, 2009, accepted March 1, 2009*)

Abstract. The purpose of this study was to determine the influence of pole carrying on the biomechanics of the run-up in the pole vault. Eight novice male pole vaulters participated and performed six 30-m sprints, three with and three without a pole. A tripod-mounted digital video camera was horizontally panned to follow the athletes from left to right and electronic timing cells recorded the sprint times. The experimental set-up recorded the average velocities and the times of the stance and swing phases; it also determined the sagittal plane angles of the hip, knee and ankle joints during a cycle. The results indicated that the average velocities during the runs were significantly lower with pole than without ($P < 0.05$). The runs with pole were characterized by significantly less flexion of the hip and knee joints at the instant of maximal hip flexion during the swing phase. Consequently, an anterior imbalance was created by running with a pole whose length was much greater than the athletes' height. This tended to increase the braking phase and decrease the stride length, causing a 'slight precipitation' by the athletes' anticipation of the foot touch-down.

Keywords: Arm swing restriction, Running, Biomechanics, Coordination.

1. Introduction

The aim of pole vaulting is to jump over a very high cross bar with the help of a long pole. Performance, which is evaluated by the vertical height attained, is directly correlated with the vaulter's final potential energy [1-4]. This energy is closely correlated with the initial kinetic energy, which reflects the horizontal velocity at take-off [5]. Thus, the pole vaulter's aim during the run-up phase is to achieve high horizontal velocity while running with the pole. Approach run velocity is significantly and linearly correlated to crossbar height. The correlation coefficients are between $r = 0.51$ to $r = 0.82$ across studies [3, 6-9] for juniors, women and men pole vaulters.

Although pole carriage during the run-up slows the athlete down in comparison with a sprint without pole [10], elite pole vaulters are able to reach the horizontal velocities of nationally-ranked sprinters. Indeed, the horizontal velocities of elite pole vaulters were between 9.10 and 10.0 m/s a few strides before take-off [11]. However, the horizontal velocity during the run-up shows a more or less stagnation 16 to 11 m before the take-off, because the athlete has to focus on the preparation of the pole plant [12]. During this part of the run-up, the pole is almost horizontal whereas the stride rate and the horizontal velocity are high.

A restriction of the arm swing during locomotion may decrease the horizontal velocity by affecting variables such as stride rate, stride length, percentage of stance phase and cycle time. According to previous studies, loading the arm [13] or carrying a rugby ball [14, 15] with both hands significantly decreased athletes' sprint velocity in comparison with a 'free' sprint. Moreover, it was suggested that a restriction of the arm swing during walking might cause an increase in the moment produced by the foot to compensate for the loss of action of the arm swing moment in balancing the lower limb swing [16]. This result suggests that a restricted arm swing may also cause an increase in the moment produced by the foot just before toe-off during running.

One of the major goals of the pole vaulter is to achieve high horizontal velocity at take-off in order to produce top-level performance. This goal is perturbed, however, by carrying the pole, because the 'carry weight' of the pole and the restricted arm swing influence the running velocity. The aim of this study was thus to determine the influence of horizontal pole carriage on run-up velocity and kinematics for novice-class pole vaulters. It was expected that the pole carriage would affect the mean velocity with a restricted lower-limb coordination. These analyses will broaden our understanding of the consequences of pole carrying on the horizontal velocity attained during the run-up.

2. Methods

2.1. Participants

Eight male students (age: 20.4 ±0.9 years, height: 178.5 ±6.0 cm, weight: 70.4 ±3.6 kg) at the Faculty of Sports Science, University of Rouen, France, were the subjects of this study. The project was approved by the ethics committee of the University of Rouen. All the participants were volunteers (the protocol was fully explained to them and they all gave their informed consent before testing began) and all were currently practising athletics. They had all had introductory classes in pole vaulting as part of their studies at the faculty and had a good high-school level in sprint. Good experience in sprint was important to ensure the reproducibility of the run-ups. All the participants carried the pole on their right side.

2.2. Pole Vault Run-Up Session

The participants were informed that they would perform a total of six run-ups: three run-ups without pole and three run-ups with pole. The length of the pole was 4.25 m and its stiffness rating was 54 kg. One researcher verbally explained and physically demonstrated the method of pole carrying. The researcher emphasized the importance of adopting a standardized pole carrying technique. The pole had to be carried on the side opposite to the take-off foot, with the front hand acting like a fulcrum and the left hand maintaining the orientation of the pole, which tends to drop down. The distance between the handgrips, subsequently measured at 59.8 cm (±5.6), corresponded to the breadth of the shoulders, whereas the angle between the ground and the pole had to be constant throughout the run-up. This angle was not high (subsequently measured at 19.9 ±7.5°) and corresponded to a pole carriage at the end of the run-up. Moreover, it also corresponded to a novice angle, allowing the subjects to be in a comfortable position and thus ensuring the reproducibility of the run-ups.

All the trials were performed in the same session. In order to avoid the effect of learning, all even-numbered athletes (participants 2, 4, 6 and 8) first performed the three run-ups without pole and then the three run-ups with pole. The odd-numbered athletes (participants 1, 3, 5 and 7) did the opposite. After being informed about the study, the participants were asked to warm-up for 10 minutes by jogging and any other exercise they wished to perform to complete it. Each participant had a 4-minute rest between run-ups. This recovery time was assumed to be sufficient [14, 17] to perform all the run-ups at maximal intensity.

2.3. Video Analysis

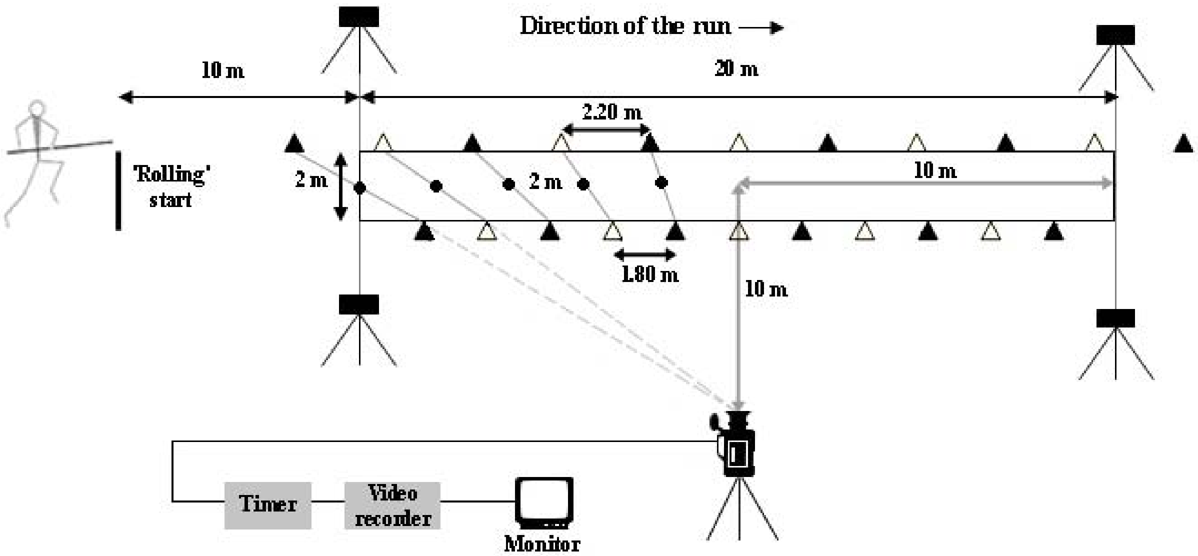

Fig.1: Schematic representation of the experimental set-up for the run-up.

The distance, corresponding to a novice run-up, over which the participants were timed was 20 m, with a 10-m ‘rolling’ start [14]. Electronic timing cells (Matsport Timing®, Brower Timing System), accurate to 1/100 of a second, were placed at 10 and 30 m to record the run-up times of the participant over 20 m. A tripod-mounted digital video camera (50 Hz, Panasonic®) was placed 10 m from both centres (longitudinal and transversal) of the recorded runway and horizontally panned to follow the athletes from left to right. The 2-m wide runway was marked by collateral plots, spaced by 1.80 m for the nearest and by 2.20 m for the farthest, which enabled the placement of 2-m markers along the longitudinal centre of the runway and counteracted the effects of parallax (Figure 1).

The digital video camera, with a shutter speed of 1/1000s, was connected to a video timer (50 Hz, FOR A®), a video recorder (50 Hz, Panasonic, NV-FS 100 HQ®) and a monitoring screen (Brandt®). Mean velocity (MV_{20}) was calculated by dividing the distance of the run-up (20 m) with the recorded time from the electronic cells. Also, three complete cycles (one in the middle of the run-up, the previous one and the next one) were used to determine mean velocity (MV_{3C}, in m/s), mean stride length (MSL_{3C}, in m/stride) and rate (MSR_{3C}, in stride/s), by counting the requisite number of video frames for these three cycles and using the 2-m markers along the runway. Using MV_{3C} and MSR_{3C}, MSL_{3C} could be calculated: $MSL_{3C} = MV_{3C} / MSR_{3C}$ [18, 19]. Average velocity was computed for each 2-m gap with the same procedure used to compute MV_{3C}.

2.4. Leg movement analysis

Markers were also placed on the body: 1) the lateral malleolus of the fibula, 2) the lateral epicondyle of the femur, 3) the anterior superior iliac spine, and 4) the base of the neck on the sternocleidomastoid muscle. These markers allowed the modelling of the participants with Dart Trainer® software (Dart Fish™, Switzerland) from the digital data of the video camera [20]. Dart Trainer® (with an accuracy of 0.1° and a calibration of ±0.5°) thus calculated the quantitative data, such as the hip, knee and ankle angles, during the right cycle (pole side) in the middle cycle of the recorded run-up. This limited the effects of parallax. These joint angles were measured at six instants during the three phases of the running cycle: (a) the stance phase at the instants of foot strike, midstance and toe-off; (b) the initial swing phase at the instant of full extension of the opposite leg; and (c) the terminal swing phase at the instant of maximal hip flexion and the instant of maximal knee extension just before foot strike. Hip flexion-extension represented the position of the femur relative to the position of the trunk. The extension of the hip was indicated by 0° when the femur and trunk were aligned in anatomical position. Knee flexion-extension denoted the angle between the femur and tibia. The full extension of the knee was indicated by 0° (180° between the femoral and tibial shafts). Dorsi-plantar flexion was the position of the foot relative to the tibia with a 90° angle being plotted as 0°.

2.5. Data Analysis and Statistics

The data were expressed as means and standard deviations of the following measures: velocity; stride length and rate; time of stance and swing phases and their percentages; and angles of flexion-extension of the hip, knee and ankle.

All the statistical tests were made using Statview® software (Abacus Concepts, Inc., Berkeley, CA, 1992). The normal distribution (Kolmogorov-Smirnov test) and the homogeneity of variance (Fisher F-test) were verified for each variable and allowed parametric statistics. Paired Student *t*-tests were used to compare the differences between run-ups without pole and run-ups with pole. For all procedures, significance was accepted at an alpha level of 0.05.

3. Results

Table 1 shows the mean velocities, stride lengths and stride rates between the run-ups with and without pole. The mean velocity of the run-ups with pole was lower ($P < 0.05$) than the mean velocity without pole, as well as for both velocities during the three cycles ($P < 0.01$). This significant difference was reflected by the finding that mean stride length was significantly smaller ($P < 0.01$) when the athlete carried a pole, whereas mean stride rate did not show any significant difference ($P = 0.26$). Table 2 shows velocities of the first, middle and last 2-m gap in the run-ups with and without pole. All the comparisons are significant, with a higher velocity of run-ups with pole than without pole for each key events of the run-ups.

Table 1: Spatial and temporal variables (means ± S.D.) of the run-ups with and without a pole.

	MV_{20}(m/s)	MV_{3C} (m/s)	MSL_{3C} (m/stride)	MSR_{3C} (stride/s)
With pole	6.12±0.44 [a]	6.31±0.46 [b]	1.56±0.12 [c]	4.05±0.29
Without pole	6.46±0.31	6.70±0.34	1.68±0.09	4.00±0.23

[a] Significant difference between both mean velocities of the run-up ($P < 0.05$); [b] Significant difference between both mean velocities for the three cycles ($P < 0.01$); [c] Significant difference between both mean stride length for the three cycles ($P < 0.01$).

Table 2: Velocities (means ± S.D.) for the first, middle and last 2-m gap during the run-ups with or without pole carriage.

	0-2 m	8-10 m	10-12 m	18-20 m
With pole	5.44±0.40[a]	6.15±0.46[a]	6.17±0.44[a]	6.33±0.50[a]
Without pole	5.76±0.30	6.45±0.36	6.57±0.36	6.78±0.37

[a] Significant difference of the given V_{2m} between both conditions of run-up ($P < 0.01$).

The video analysis revealed that the phase between foot strike and midstance (= the braking phase) was longer ($P < 0.05$) when the athlete carried a pole compared with run-ups without pole. This significantly longer braking phase induced a significantly ($P = 0.02$) longer stance phase. Moreover, the maximal hip flexion occurred significantly later ($P < 0.05$) during the run-ups with pole than without pole (Figure 2). The pole-side cycle showed that the maximal hip flexion angle ($P < 0.01$) and the maximal knee flexion angle ($P < 0.05$) were significantly smaller during the run-ups with pole than without pole, whereas no significant difference was noted for the dorsi-plantar flexion between the two conditions of run-up (Figure 3).

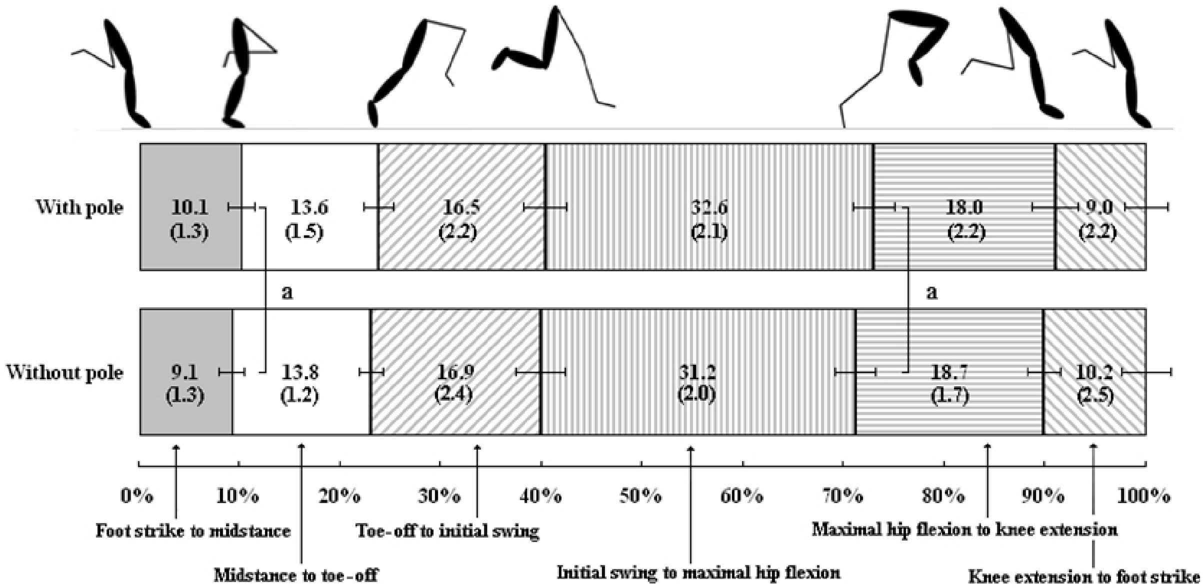

Fig. 2: Mean percentages (S.D.) of the different phases of the pole-side cycle. [a]: Significant difference ($P < 0.05$).

4. Discussion

The results showed that carrying a pole during the run-up had a significant effect on the horizontal velocity and that the decrease in this velocity was correlated with a significant decrease in stride length, whereas the stride rate was relatively unchanged.

The studies by Linthorne [21, 22] determined that the run-up velocity of elite pole vaulters was 0.5 m/s less than in the long jump at the end of the run-up. As a consequence, the difference in the run-up velocity was about 4.5% between the two conditions of run-up (with and without a pole). The present study revealed an absolute difference in velocities similar to that reported by Linthorne (0.5 m/s *vs* 0.45 m/s, for Linthorne's studies and our study, respectively). But the relative difference was much larger (6.6%) between the conditions of run-up, which was consistent with the findings in the literature [21, 22]. The results in relation to Linthorne's findings may also suggest that the difference in run-up velocity decreases with the increase in the level of practice. Moreover, these results are in accordance with a previous study [14], where a significant decrease in sprint speed was determined when athletes carried a rugby ball with both hands compared with a 'free' sprint. The authors suggested that the restriction of movement in both arms resulted in limitations to the biomechanical characteristics for good sprinting. Indeed, a strong arm drive allows the body to counteract the pelvic movements and, consequently, the body will be balanced during sprinting [23].

These results also confirm that, for running velocities under 7 m/s, a decrease in velocity is associated with a decrease in stride length before a decrease in stride rate [24]. Previous authors [24-26] demonstrated that stride rate and stride length increased with the increase in velocity, but not linearly. The increase in stride length largely contributed of the increase in velocity at a submaximal level. At supramaximal velocity (108.4%), stride rate contributed 6.9% and stride length 1.5% [26]. In our study, although the difference in stride rate was not significant, running with a pole induced a stride rate slightly higher than the stride rate of the run without a pole, whereas the horizontal velocity was significantly lower. In other words, the novice pole vaulter tried to compensate the losses in velocity and stride length by an increase in stride rate. Moreover, our novice athletes were instructed to reach optimal sprint velocity for both run-ups (*e.g.* as in long jump for the 'without pole' condition). This may explain why stride rate did not significantly differ between conditions, because velocity and stride length irremediably decreased when the novice athletes ran with a pole.

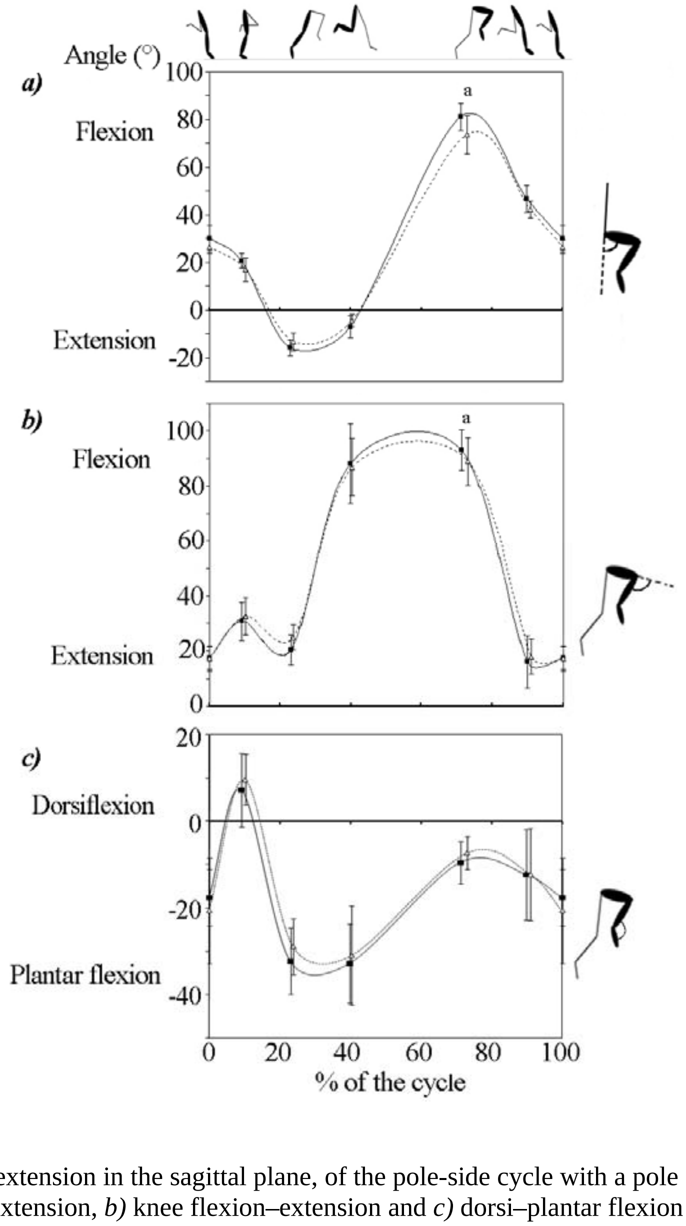

Fig. 3: Angles of flexion–extension in the sagittal plane, of the pole-side cycle with a pole (dotted line) and without (solid line); *a)* hip flexion–extension, *b)* knee flexion–extension and *c)* dorsi–plantar flexion of the ankle. [a]: Significant difference ($P < 0.05$).

In accordance with earlier studies [23, 26, 27], the stance phase decreased with the increase in velocity. However, pole carrying has some specific features. The results of our video analysis indicated a significant longer stance phase due to a longer braking phase for the run-ups with a pole. According to previous studies [26, 27], an increase in the braking phase was observed during a decrease in the sprint velocity. Moreover, an increase in hip flexion was related to a reduction of the braking forces during ground contact, *i.e.* a faster leg recovery allowed a better position to initiate a foot backward acceleration relative to the direction of the whole body just before foot-contact [28]. In considering that stride length was correlated with increase in the maximal hip flexion during the swing phase [29], the present study, demonstrated that the loss in run-up velocity can be explained by this loop-phenomenon: the lower hip flexion caused a higher braking phase, which both resulted in a lower stride length.

This loop could be a part of another phenomenon. The centre of gravity (CG) of the pole-athlete system is in a front of the CG of the athlete alone (*the forward displacement*). This forward displacement of the CG was revealed by a static baropodometric analysis (Delval, unpublished data). Without pole carriage, CG was projected at a navicular level whereas with a pole the CG was at a metatarsal level. From a recent running model [30], the position of the athlete's CG relative to his foot on the ground created the moment arm of a gravitational torque, which produced stride length from horizontally accelerating body. The authors stated that if the body was accelerating from the gravitational torque (fall forward), there was no need to push-off with the stance leg. In relation to our study, this model could explain that the forward displacement of the CG, by carrying a pole, allowed the vaulter to have no significant difference in leg extension (Figure 3*a* and 3*b*), at toe-off, compared to a 'free sprint', although the velocity was significantly lower. But, the forward displacement of the CG could be too high and could generate a too large gravitational torque, which did not allow the pole vaulter to have enough time to recover the swing leg in a way to accelerate the foot before ground-contact. In the light of our results and of the gravitational model [30], pole carriage did not allow the novice athlete to have a balanced position to anticipate the ground-contact and accelerate the foot just before this time.

Video analysis showed another effect of pole carriage on the kinematics, which explained the drop in velocity. Indeed, the maximal knee flexion of the run-ups with a pole was significantly less than during the run-ups without a pole. As already observed, the greater the knee flexion during the swing phase was, the greater the decrease in the moment of inertia was, allowing a faster swing of the 'free' leg [29]. The maximal knee flexion thus increased with the sprint velocity. This result, associated with the lower hip flexion, strengthens the idea that athletes tend to precipitate and not anticipate the touch-down during a run-up with a pole. This 'slight precipitation' resulted in a decrease in stride length and an increase in the stance phase, causing the lower velocity of the run-up.

For the purpose of this study, the effects of pole carriage were determined in novice pole vaulters with a constant pole-ground angle throughout the run-up. However, most world-class vaulters use a pole drop technique, in which the pole is held almost vertically at the start of the run and is then gradually dropped during the run-up so that it falls into the vault box at the end of the run. This technique reduces the effects of the moment caused by the weight of the pole but results in different sprint kinematics and requires additional control and vigilance. It thus offers an advantage only to expert pole vaulters. We chose to keep a constant pole-ground angle throughout the run-up for several reasons: 1) it is simpler, without the need for additional control and vigilance, thus ensuring greater reproducibility in novice run-ups, 2) the run-ups with and without pole carriage are more easily compared because the effect of a varying pole-ground angle on the sprint kinematics is eliminated and 3) for novice as well as for expert pole vaulters, the pole is carried at the horizontal whereas the velocity is high in the final part of the run-up. However, understanding the effect of this varying pole-ground angle would be useful in determining which pole position is most appropriate for producing high horizontal velocity during the run-up. Moreover, this research indicates some future perspectives. Indeed, it would be interesting to determine whether the differences between the 'free' run-up and the run-up with pole carriage are the same under all conditions, such as the run-ups of elite pole vaulters or those performed with poles of varying lengths and stiffness.

5. Conclusion

In conclusion, the aim of this study was to determine the influence of pole carriage on run-up velocity and kinematics for novice-class pole vaulters. The results demonstrated that the athletes were negatively affected by pole carriage, notably by a loss in sprint velocity due to the significant decrease in stride length and the increase in the braking phase. The athletes seemed to develop an anterior imbalance because of the constraint imposed by forward displacement of the CG. Finally, this study points out the relevant consequences of pole carriage on the run-up kinematics for novice pole vaulters using readily available equipment.. Thus, this experimental protocol could be used to establish a reference in the context of training assessment or longitudinal training support to follow the improvement of novice athletes. Moreover, training programs, especially for novice pole vaulters, should perhaps incorporate a large range of exercises with pole carriage, including sprinting, jumping and hopping on one foot. All these exercises would have the same goal: to improve sprint velocity and strengthen posture with a pole in the hands.

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