COMPARISON OF STEP CHARACTERISTIC INTERACTION AND ASYMMETRY BETWEEN FAILED AND SUCCESFUL ATTEMPTS IN POLE VAULT

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The purpose of this study was to investigate step characteristics of high level pole vaulters during failed and successful jumps in terms of: a) the direction and magnitude of asymmetry between the pole carrying (PC) and non-pole carrying (NPC) foot and b) the reliance of step velocity (SV) on either step frequency (SF) or step length (SL). Eight male pole vaulters were recorded during competition with a panning video camera operating at 300 fps. Asymmetry was observed in four vaulters on either SF or SL both in successful and failed attempts but it was not consistent and its direction was not related to the athletes' PC limb. No athletes demonstrated significant asymmetry for SV between failed and successful jumps. At the highest jump cleared, five out of eight vaulters demonstrated SF reliance. However, as the failed attempts progressed vaulters became less SF reliant.

KEY WORDS: step length, step frequency, step velocity, approach run, reliance.

INTRODUCTION: During the approach run in pole vault, the main objectives are to obtain a large horizontal velocity and to prepare for the planting of the pole. (Adamczewski & Perlt, 1997; Angulo-Kinzler et al., 1994; Frere, L'Hermette, Slawinski, & Tourny-Chollet, 2010). The velocity of the vaulter increases through the plant preparation phase, where maximum approach speed is achieved, facilitated by the "moment-free" lowering of the pole that allows the vaulter to increase step frequency (SF) to a greater extent than step length (SL) (Gros & Kunkel, 1986; Petrov, 2004). It is widely accepted that step velocity (SV) is considerably influenced by SL and SF (Salo, Bezodis, Batterham & Kerwin, 2011). Consistency in step characteristic interaction in each jump attempt ensures that the vaulter's precise movement patterns can be repeated with minimal deviation throughout the competition. Hovewer, Tamura, Nunome & Usui (2016) observed a clear difference in gait regulation strategy between successful and failed vaults.

A further source of interaction between SL and SF, while trying to regulate velocity during the approach run, is bilateral asymmetry and the possible prevalence or preference of a limb for performing this task. Sprinting mechanics alter when carrying a pole, due to the created anterior imbalance (Frere, Chollet, & Tourny-Chollet, 2009). Additionally, the carriage of the pole restricts arm swing while its relative weight adds gravitational torque which reduces recovery time for the swing leg and its ability to accelerate the foot before ground contact (Frere et al., 2009). Furthermore, the positioning of the pole to one side of the athlete during the approach run leads to asymmetrical arm positioning. However, although carrying the pole produces a less efficient run during the acceleration, Theodorou, Panoutsakopoulos & Exell (2016) reported that elite pole vaulters appear to increase their velocity by increasing SF to a greater extent than SL and that the asymmetrical demands of pole carriage and planting do not cause step velocity asymmetry.

The aim of the study was to investigate step characteristic changes of pole vaulters during competition, with the objectives of identifying a) differences in step characteristics, b) the direction and magnitude of step characteristic asymmetry, and c) step characteristic reliance during failed and successful jumps. It was hypothesised that around each athlete's performance limits, asymmetry would increase (H_1) and SF reliance would decrease (H_2) during failed jumps compared with the final cleared jump.

METHODS: Following institutional ethical approval and permission from the organising committee, data were collected during the 2015 Athens Street Pole Vault European Athletics Association meeting. The sample comprised 8 male elite pole vaulters (age = 25.2 ± 3.9 yrs, height = 1.85 ± 0.05 m, mass = 78.0 ± 5.7 kg, personal best performance = 5.68 ± 0.21 m), who consented to take part in the study. Spatiotemporal data of the approach run were collected using a panning camera (Casio EX F1, Casio Computer Co. Ltd., Shibuya, Japan) at a sampling rate of 300 fps. Markers were placed at 1 m intervals along the runway lines. The camera was zoomed in on the athletes' feet and manually panned to allow the final phase of the run-up to be recorded. Videos were manually digitised (APAS 13.3.0.3.; Ariel Dynamics, Inc., Trabuco Canyon, CA). Step characteristic reliance analysis was performed at each athlete's best jump at the competition and the three unsuccessful attempts that followed that jump (in total 8 x 4 = 32 attempts); however, Athlete 8 did not attempt a third jump after their highest clearance, resulting in 31 analyses. The variables identified were SL, SF and SV for each step from the 9th up to the 2nd to last step of the approach run. Athletes were identified as being SF or SL reliant using the bootstrapping technique outlined by Salo et al. (2011). Asymmetry of step characteristics was analysed for all cleared jumps and all failed attempts separately for each athlete. Asymmetry values were quantified between mean values for steps following pole carrying (PC) foot take-off (PC-NPC) and steps following non-pole carrying (NPC) foot take-off (NPC-PC) for each athlete. Asymmetry was quantified using the symmetry angle (θ_{SYM}) method (Zifchock, Davis, Higginson, & Royer, 2008) taking into account intra-limb variability (Exell, Gittoes, Irwin & Kerwin, 2012). Additionally, a 2 (cleared / failed attempts) x 2 (non / pole carrying foot) x 8 (step number) ANOVA with repeated measures on step number was run using the IBM SPSS Statistics v. 21.0 for Windows software (IBM Corp., Armonk, NY) in order to check possible SL, SF and SV differences.

RESULTS: Mean values of PC and NPC step characteristics are presented in Table 1. Four out of eight athletes (M2, M5, M6, M8) exhibited significant asymmetry during their total approach run in SL and/or SF between PC-NPC and NPC-PC steps. No athletes demonstrated significant SV asymmetry. At the highest jump cleared (Figure 1a), five out of eight athletes demonstrated SF reliance (M2, M3, M5, M7, M8), with the other three athletes favouring neither characteristic. However, as the failed attempts progressed (Figure 1b-d) athletes became less SF reliant with just one athlete (M7) remaining SF reliant during their final attempt, with the others being reliant on neither SF or SL.

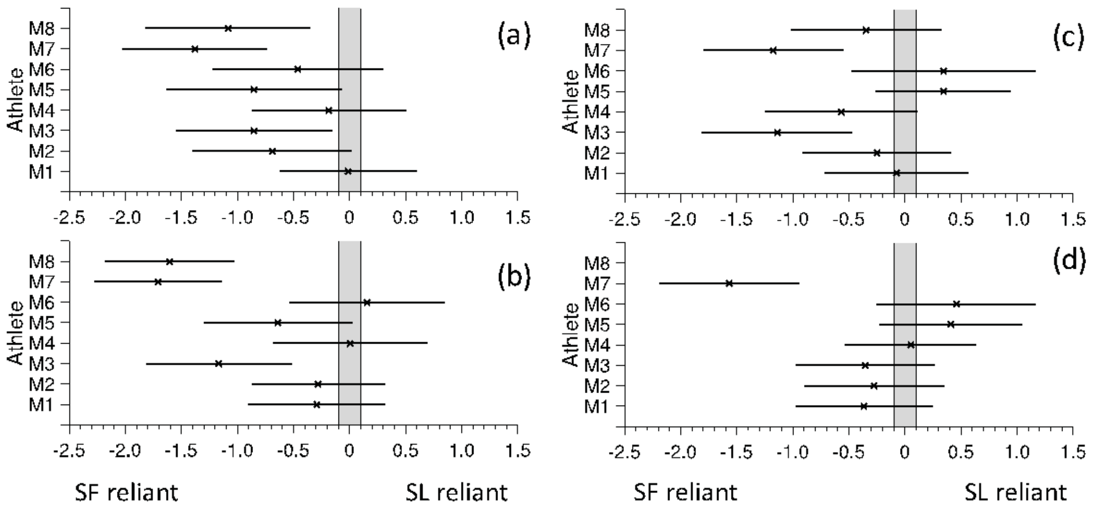

Figure 1: Differences in SL-SV and SF-SV relationships (Pearson r), along with 90% confidence interval bars during the approach phase. The area of ±0.1 is shaded to indicate the boundaries for non-reliance on either characteristic. (a = cleared jump, b-d = failed jump 1-3).

Table 1
Step characteristics for highest cleared and failed (mean of 3 failed) jumps for each athlete

Athl.	Jump Result	Bar Height (m)	Step Velocity (m/s)			Step Length (m)			Step Frequency (Hz)		
			NPC	PC	θ_{SYM}	NPC	PC	θ_{SYM}	NPC	PC	θ_{SYM}
M1	Clear	5.54	9.12	9.30	0.60	2.24	2.26	0.28	4.08	4.13	0.35
	Fail	5.64	9.28	9.43	0.51	2.27	2.27	-0.00	4.09	4.16	0.53
M2	Clear	5.24	8.48	8.38	-0.34	2.09	2.03	-0.94*	4.06	4.13	0.59
	Fail	5.34	8.46	8.39	-0.25	2.11	2.07	-0.61	4.02	4.06	0.35
M3	Clear	5.34	8.56	8.75	0.73	1.97	2.09	1.78	4.34	4.21	-0.96
	Fail	5.44	8.72	8.82	0.34	2.02	2.03	0.22	4.33	4.36	0.17
M4	Clear	5.64	8.63	8.59	-0.15	2.30	2.21	-1.33	3.75	3.89	1.19
	Fail	5.74	8.18	8.60	1.62	2.15	2.21	0.74	3.79	3.90	0.98
M5	Clear	5.34	8.62	8.77	1.57	2.11	2.24	1.85	4.09	3.93	-1.28
	Fail	5.44	8.97	8.30	2.50	2.17	2.10	-1.05	4.12	3.94	-1.33‡
M6	Clear	5.44	8.62	8.96	1.23	2.38	2.30	-1.18	3.62	3.90	2.36*
	Fail	5.69	8.65	8.85	0.73	2.39	2.33	-0.75	3.66	3.80	0.96‡
M7	Clear	5.34	8.88	8.83	-0.19	2.28	2.28	0.00	3.90	3.88	-0.18
	Fail	5.54	8.84	8.77	-0.25	2.27	2.28	0.15	3.91	3.86	-0.38
M8	Clear	5.54	8.69	8.40	-1.06	2.28	2.42	1.83*	3.81	3.48	-2.84
	Fail	5.64	8.65	8.35	-1.13	2.28	2.36	1.05‡	3.80	3.55	-2.22
ALL	**Clear**	***5.44***	***8.70***	***8.75***	***0.17***	***2.21***	***2.26***	***0.23***	***3.96***	***3.94***	***-0.45***
(*n*=8)	**Fail**	***5.56***	***8.72***	***8.69***	***-0.12***	***2.21***	***2.21***	***-0.03***	***3.97***	***3.95***	***-0.12***

NPC= non-pole carriage to pole carriage step, PC = pole carriage to non-pole carriage step, θ_{SYM} = symmetry angle, * = significant asymmetry for cleared jump, ‡ = significant asymmetry for one of the three failed jumps only.

Finally, non-significant ($p > .05$) differences were revealed between cleared and failed attempt and between NC and NPC on SL, SF and SV. At both cleared and failed attempts, SF for 2nd-, 3rd-, 4th- and 5th- to last steps was significantly larger ($p < .05$) compared to 7th-, 8th- and 9th to last steps. Finally, at the failed attempts, SL for 2nd-, 3rd- and 4th- to last steps was significantly larger ($p < .05$) than the 9th-to last step. This result was not evident for the cleared jumps.

DISCUSSION: The aim of the study was to investigate step characteristic changes of pole vaulters during competition. Step characteristics were not different between cleared and failed attempt and between NC and NPC. The asymmetry analyses of step characteristics did not reveal a consistent trend across the athletes both in successful and failed attempts. Two athletes (M2, M8) displayed significant asymmetry for SL and two (M5, M6) for SF. The direction of asymmetry was not related to the athletes' PC limb, with one athlete each displaying greater SL (M8) and SF (M6) for the PC limb and one athlete each displaying greater SL (M2) and SF (M5) for the NPC limb. Despite the unilateral task constraint of pole carriage and planting, no athletes demonstrated significant asymmetry for SV both in successful and failed attempts. The absence of SV asymmetry and magnitude of SL and SF asymmetry is similar to that reported in high level long jumpers (Theodorou et al., 2016) and considerably less compared to sprint running (Exell et al., 2012). Therefore, H_1 was rejected for asymmetry.

Furthermore, the results suggest that at their best successful jump, pole vaulters increase their velocity by increasing SF to a greater extent than SL during late approach. However, when attempting to clear greater heights, athletes were less reliant on SF to increase SV, leading to H_2 being accepted for step characteristics. This change in SF reliance could be attributed to a possible change at the stiffness of the poles. As the athletes progressed from the last successful height to the next one (and eventually failed) the length of the pole remained the same but its stiffness was increased. Although, the relative weight of the pole and the resultant gravitational torque is unlikely to have changed, it is probable that the athletes knowing that they have to transfer a greater amount of energy to bend the pole subconsciously tried to increase their SV by changing the usual pattern of their step characteristics.

CONCLUSION: The lack of asymmetry in SV may be attributed to the task constraints of the event. The specific number of steps, rhythm of velocity attainment, accuracy of take-off foot placement and pole planting are all parameters that constitute parts of the visual regulation process. This confirms that most vaulters have fairly constant stride patterns and velocities throughout the competition (Gros, Adamczewski, & Wolf, 1994). The shift of SV reliance away from SF to neither SF or SL as the failed attempts progressed needs to be further examined in association with pole stiffness characteristics and the physical conditioning of the athletes.

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Acknowledgement
The authors wish to thank the Organizing Committee of the 2015 Athens Street Pole Vault permit meeting for allowing the conduction of the study.