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Patterns of locomotor regulation during the pole vault approach phase

Laurie Needham, Timothy A. Exell, Ian N. Bezodis, and Gareth Irwin

Abstract:

A successful approach phase is key to achieving high performances in the pole vault. The aim of this study was to explore the nature of locomotor control patterns during the pole vault approach phase. Fourteen well-trained athletes performed ten jumps which were recorded using 2D video sampling at 200 Hz and analysed. Key kinematics were reconstructed from camera data using a modified 2D-DLT. Patterns of regulation were determined from the standard deviation of footfall locations during the approach phase. These patterns were found to be highly individual but structural differences between those who did and those who did not regulate were identified. Regulation of locomotion was associated with an ability to produce functionally adaptable movement patterns and the consistent achievement of desired performance outcomes. Coaches should include training exercises that require intentional use of regulation to aid athletes in achieving the flexibility to adapt to changing constraints during the approach phase. Athletes should be considered on an individual basis in order to effectively, efficiently and safely improve performance.

Keywords: Pole vault, approach phase, regulation, adaptability.

Introduction:

Pole vaulting requires athletes to clear a high horizontal cross bar using a flexible vaulting pole. In order to achieve the correct take-off characteristics and maximise the potential to be successful the athlete must satisfy a number of demands during the approach phase. These include concurrently achieving a high horizontal velocity, coordinating the lowering of the pole into the plant box and consistently achieving an accurate take-off position. Various studies have examined different aspects of the pole vault from kinematics (Hay, 1994; Angulo-Kinzler et al., 1994), energetics (Schade, Arampatzis & Brüggemann, 2000; 2004; 2006), and simulation (Hubbard, 1980; Ekevad & Lundberg, 1995; Liu, Nguang & Zhang, 2011) perspectives. Previous research has established that greater peak heights are associated with high horizontal velocities during the approach phase (Greig & Yeadon, 1997; Adamczewski & Perlt, 1997; Frere et al., 2010). Frere et al. (2009) concluded that pole carriage caused decreases in running velocity (6.6%) as a result of significantly reduced step lengths in novice athletes, but these finding were from an unconstrained run with no requirement to achieve a desired take-off location or perform the rest of the jump.

A reconceptualisation of pole vault performance can be derived from the constraints lead approach (McGinnis & Newell, 1982) which considers the interaction of the athlete, task and environment, based on the Dynamical Systems Theory (DST) (Newell, 1986). Unique to pole vault is the task constraint, created by the need to carry and coordinate the lowering of a vaulting pole and the spatio-temporal constraint created by the necessity to take-off in a specific location (plant box) with the absence of a visual and physical target (e.g. take-off board in long jump and triple jump (Lee, Lisham & Thompson, 1982; Hay & Koh, 1988).

The need for the athlete to achieve a precise and consistent take-off location is essential for success. This consistency at take-off can be considered to correspond to the concept of low end-point variability of footfall location, which is considered to be a key performance factor within pole vault coaching literature (Richardson, 2012) as well as for wider gait-regulated disciplines such as long and triple jump (Hay & Koh, 1988). Consistent performance outcomes can be achieved by different patterns of coordination (Bernstein, 1967) and as such, movement pattern variability can be considered functional if it permits the performer the flexibility to adapt to changing constraints during goal-directed actions (Barris, Farrow, & Davids, 2014). The concept of degeneracy provides the theoretical framework to explain functional movement variability and provides athletes with robustness against perturbations (Whitacre & Bender, 2010; Davids et al., 2013; Seifert et al., 2013). Movement patterns can be continuously adapted in a functional way to allow skilled consistent performance outcomes rather than attempting to utilise rigid, stereotyped movement patterns (Barris et al., 2014). Evidence from gait-regulated tasks such as triple-jump (Wilson et al., 2008) demonstrates that individuals are capable of finding different ways to achieve the same performance outcome, even under similar task and environmental constraints. In gait-regulated tasks such as the pole vault approach phase, it has been proposed that performers make adjustments through visual control mechanisms (Lee et al., 1982; Hay, 1988; Glize & Laurent, 1997; Bradshaw, 2004) where by the athlete uses perceptual reference points close to the target to control locomotion. This visual information provides a continuous regulation process based on a perception-action coupling (Montagne, Cornus, Glize, Quaine, & Laurent, 2000). Locomotor control mechanisms have been explored extensively within gait-regulated tasks such as

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long jumping, gymnastics vaulting and walking tasks, and appear to be present across populations, regardless of the athlete's level of skill (Bradshaw & Aisbett, 2006), age (Berg et al., 1994, Panteli et al., 2014), or familiarity with the task (Scott et al., 1997). Typically these control mechanisms have been studied using spatio-temporal variables such as changes in step length and footfall location variability (Lee, Lisham & Thompson, 1982; Hay, 1988) with additional insight being provided by the assessment of the relationship between the adjustments in step length required and adjustments produced to successfully complete the task (Montagne et al., 2000).

In the context of pole vaulting, little is known about the approach phase which is more complex in nature than previously studied tasks (e.g. walking, long jump, gymnastics vault etc.) due to additional constraints such as pole carriage, discussed above, and a higher risk of serious injury should the task not be completed correctly. Some evidence (Hay, 1988) exists to support the notion that elite male pole vaulters utilise similar control strategies to other gait regulated tasks but further research is required to assess and understand the strategies of elite and developing skill levels. The aim of this study was to explore the nature of locomotor control patterns during the pole vault approach phase. The purpose of gaining this information was to inform coaches when prescribing approach phase training exercises. It was hypothesised that athletes would present individual patterns of locomotion regulation during the pole vault approach phase.

Methods:

Participants

Ethical approval was granted by the University's Research Ethics Committee and all participants provided written informed consent. Eleven male (mean ± SD age: 21 ± 4 years, height: 1.85 ± 0.07 m, mass: 76.7 ± 12.7 kg) and three female athletes (mean ± SD age: 17 ± 3 years, height: 1.63 ± 0.02 m, mass: 60.9 ± 6.25 kg) were recruited. Performance level was assessed against the current senior world record. Male personal bests ranged between 70% and 90% of the world record while female personal best ranged between 65% and 80% of the world record.

Experimental set-up

Data collections were conducted during a single session at an indoor athletics centre. Kinematic data were collected using four HDV cameras (Type HVR – Z5E; Sony, Japan) placed at a perpendicular angle, 25 m from the approach runway (Figure 1). A sample rate of 200 Hz was selected with a shutter speed of 1/425 s and an open iris. Calibration of the performance area was achieved using a single object of known distances placed sequentially alone the centre of the runway to create a 40 m x 3 m plane. Additional recordings were made with a second object consisting of markers of known distances in order to test accuracy and precision of reconstruction.

**************** FIGURE 1 NEAR HERE *****************

Anthropometric data were collected before participants conducted a self-selected warm-up similar to that normally used during their training sessions. Each participant was required to perform ten jumps over an elastic training bar set between 95-98% of their personal best from a full approach run of self-selected distance. Bar height was determined following discussions with national level coaches. This height range was selected to encourage athletes to perform a regular jump without invoking performance changes that might be associated with attempting to perform jumps at maximal or substantially submaximal heights. Successful jumps (where the athlete attempted to complete a full jump over the bar) were assessed qualitatively by an experienced national level pole vault coach who was present at all data collections. Any trial that was qualitatively deemed to be unsuccessful was discarded. Participants were instructed to allow for full recovery between trials. The number of attempts required to complete the requisite number of jumps was recorded for each athlete. This data was used to determine success rate.

Data Analysis

Camera images were imported to MATLAB (V2013b; The Mathworks Inc. Natick, USA) where an open source digitisation toolbox (Hedrick, 2008) was used to locate the position of desired landmarks. These landmarks included the vertex, C7, hip, shoulder, elbow, wrist, knee, ankle, MTP joint centres and proximal and distal end of the pole. A modified 2D-Direct Linear Transformation (DLT) (Woltring & Huiskes, 1990) was used and a ninth parameter was added to account for the non-linearity of the lens in accordance with Walton (1981). Total body centre of mass (CoM) locations in the vertical (z) and horizontal (y) axes were calculated using de Leva's (1996) model. CoM location of the foot segment was calculated using Winter's (2009) model with an additional mass, determined by weighting each participants shoe, added to account for each individual's footwear mass (Bezodis, 2008). Additionally, pole mass and CoM locations were ascertained using a balance test.

For each participant, spatio-temporal characteristics including step velocity (SV), step length (SL) and step frequency (SF) were calculated in accordance with Bezodis et al., (2008). Instances of touch-down and toe-off were identified in order to calculate the duration of ground contact time (GCT) and flight time (FT). Between-trial variability of the toe-to-plant box distance were assessed via the standard deviation of each footfall location in the y-direction (SD_{ff}).

Participants were grouped post-hoc as either regulators or non-regulators utilising the regulation definitions of Hay (1988) and Berg et al. (1994). Examples of each pattern are provided in figure 2. These definitions were as follows:

- Ascending/Descending Pattern (A/D) – An overall increase in the SD_{ff} proceeded by a marked and systematic decrease in $SD_{ff.}$
- Ascending Only (AO) – Only, a systematic increase in SD_{ff} is observed.
- Random Fluctuations (RF) – Small, random-like fluctuations are present in SD_{ff} throughout the approach phase.

Based upon these definitions participants were grouped, post-hoc as either regulators or non-regulators. Step numbers are denoted so that 'final' represents the final ground contact, 'penultimate' represents the step immediately preceding the final step, '-3' represents the step preceding the penultimate step… and so on.

************ FIGURE 2 NEAR HERE **************

In accordance with previous gait regulation research (Hay, 1988; Montagne et al., 2000; Renshaw & Davids, 2004) SD_{ff} for each step, the distribution of adjustments for the final six steps and an intra-step analysis of adjustment required and adjustments produced for the final six steps were calculated. SD_{ff} profiles for each step allow for consistency of footfall placement to be mapped across the entire approach phase. Due to the differing approach lengths utilised by participants (12-18 steps) data presented in Figure 3 were time normalised to 101 data points in order to clearly present each individual's SD_{ff} pattern. 0% represents the first footfall location of the approach phase i.e. at the end of the first step and 100% represents the end of the approach phase i.e. the take-off step.

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Intra-step analysis was conducted by assessing the relationship between the magnitudes of step adjustments required and produced. Adjustment required (Adj_R) were calculated as the difference between the mean footfall location across all trials and the actual footfall location for a given step. Adjustments produced (Adj_P) were calculated as the difference between the mean step length across trials and the actual subsequent step length (Montagne et al., 2000). Linear regression analyses were utilised in order to assess the extent to which performers were capable of producing the required amount of adjustment for each step of the run-up. A Shapiro-Wilk test confirmed that data were normally distributed.

In order to explore the underlying structure of variables discussed above for each group, a principle components analysis (PCA) was implemented. Input variables were selected based upon the underlying theory (Hair et al., 2010) utilising variables that describe locomotor regulation during the approach phase. Eight variables were loaded into the PCA input matrix (CoM Velocity, SL, SF, GCT, FT, SD_{ff}, Adj_R, Adj_P). Sampling adequacy was confirmed using a Kaiser-Meyer-Olkin test. For each group, data were processed for a PCA using a custom written script in MATLAB (V2016a; The Mathworks Inc. Natick, USA). The number of principle components required to explain 95% of the variance in the data were computed using a Scree test criterion. For each of these identified principle components (PC), a set of component coefficients were also produced. Component coefficients represent the correlation coefficients between the variables and the principles components. Component loadings exceeding ±0.4 were considered to indicate significant loading (Hemphill, 2003) and any variable which was similarly correlated to multiple components was considered to cross-load, and was therefore discarded from the analysis.

Results:

SD_{ff} patterns that were identified to match the A/D pattern (n = 8) were deemed to show evidence of regulation while patterns matching either the R/F (n = 3) or A/O (n = 3) pattern were deemed to not show evidence of regulation based upon this measure. Example SD_{ff} patterns for each regulation definition are shown in figure 2. For the regulation group, 94% of jumps were deemed to be successful while for the non-regulation group, 54% of the jumps were deemed to be successful.

*********** FIGURE 3 NEAR HERE ****************

For the regulation group mean take-off location accuracy was 0.10 m ± 0.04 m with a maximum SD_{ff} during the approach of 0.15 m ± 0.05 m, while for the non-regulation group, mean take-off location accuracy was 0.09 m ± 0.05 m with a maximum SD_{ff} during the approach of 0.09 m ± 0.05 m. The step for the onset of regulation for the regulation group was between step -5 and -2 while no such step could be identified for the non-regulation group.

Intra-step regression analysis described the linear relationship between the amount of Adj_R and the amount of Adj_P. In the regulation group intra-step analysis revealed statistically significant correlation coefficients (p <0.05) between Adj_R and Adj_P at the penultimate and final steps (Figure 4, left). No correlation coefficients were found to be significant in the non-regulation group (p >0.05) at any step (Figure 4, right).

************ FIGURE 4 NEAR HERE ***************

Results of the PCA analysis showed that at least 95% of the variance was accounted for in six and five principle components for the regulation group and non-regulation group respectively. The first principle component accounted for 38% of the variance for the regulation group and 39% of the variance in the non-regulation group.

******** TABLE 1 NEAR HERE ********

For the regulation group (Table 1), PC1 and PC3 were most heavily loaded with variables which represent regulation of locomotion (i.e. SD_{ff} and SL on PC1 and Adj_P and Adj_R on PC3). CoM Velocity was found to cross-load between PCs and was discarded. In contrast for the non-regulation group (Table 1), CoM Velocity loaded heavily on PC1. SD_{ff} and Adj_P were cross loaded between PCs.

Discussion and Implications:

Based on the underlying mechanics of the pole vault approach phase and applying the paradigm of Dynamical Systems Theory (DST) this study aimed to explore the nature of locomotor control patterns during the pole vault approach phase. The purpose was to add to the knowledge of regulation of locomotion during complex skills and to inform coaches who prescribe approach phase training exercises.

Pole vaulters in this study demonstrated three distinct patterns off SD_{ff}. The majority of pole vaulters in this sample (n = 8) presented an A/D pattern while A/O (n = 3) and R/F (n = 3) patterns were less common. These findings align with previous research in similar gait regulated tasks such as long jumping where the A/D pattern was most common (Hay & Koh, 1988). The A/D pattern was remarkably similar to that observed in previous long jump studies (Lee et al., 1982; Hay & Koh; Scott et al., 1997; Panteli et al., 2014) in terms of the presence of an ascending/descending pattern and the onset point of regulation. This suggests that the majority of pole vaulters did regulate locomotion to achieve a desired take-off location.

Regulation patterns do not appear to be associated with skill level here given that the top two performers in this sample presented different patterns. Further to this, performers who demonstrated an R/F pattern presented very low levels of variability throughout the approach phase, demonstrating that high performance levels can be achieved through the use of differing regulation strategies. The R/F regulation strategy is the closest to a stereotyped movement pattern i.e. an approach run with the absence of variability (Richardson, 2013). However, this strategy may lack robustness as these participants do not demonstrate an ability to make functional adjustments during the approach phase, which may be required to ensure success through take-off position consistency. Movement system robustness or the ability to functionally adapt to perturbations in the task are commonly associated with expert behaviour (Seifert et al., 2013). Expert performance has been associated with stable movement patterns that are not stereotyped and rigid but flexible and adaptable, since neurobiological systems can exploit inherent degeneracy (Edelman & Gally, 2001). These concepts are further supported when success rates are considered, see results section. Those who showed evidence of adaptability, i.e. were able to produce a stable movement pattern when needed or a flexible movement pattern when needed (Seifert et al., 2013), achieved a 94% success rate (A/D pattern - regulation group). In contrast, those who showed evidence of a rigidly stable and inflexible movement pattern (A/O or RF pattern - non-regulation group) achieved a 54% success rate. On this basis, the post hoc grouping utilised in this study seem justified. It should be noted that all trials presented in this study were successful ones which may in part explain the similarities in take-off location accuracy between groups.

Correlations analysis between Adj_R and Adj_P revealed significant relationships for the penultimate and final steps in the regulation group only. Given that the non-regulation group did not show evidence of regulating or adjusting gait it is unsurprising that no significant correlations were observed. Adjustments produced by the regulation group occurred later during the pole vault approach phase, than during the long jump approach phase (Montagne et al., 2000; Panteli et al., 2014) where a significant correlation was noted at every step after the onset of regulation (approximately six steps from take-off). This later onset of regulation for pole vaulters may be attributed to the reduced accumulation of variance in footfall location (0.15 m) when compared to long jumpers (0.23 m for elite performers (Hay, 1988); 0.29 m for junior performers (Berg *et al*., 1994)). Lower variability in footfall locations would therefore reduce the demand for regulation. When the pole vault approach phase is considered in the context of a perception-action couple (Glize & Laurent, 1997; Montagne et al., 2000), perceptual information that signifies the need to produce adjustments would be expected to arrive later in the approach phase when magnitudes of variability are lower.

The influence of pole carriage upon regulation of gait remains unclear. Where the pole vaulter experiences greater constraints due to the demands of coordinating the lowering of the pole, the flexibility to adapt to local conditions may be limited. Additionally, the high risk of injury associated with not achieving the correct take-off location cannot be ignored (Rebella et al., 2008; Boden et al., 2012). While an inability to adapt and produce adequate adjustments during a long jump approach phase may lead to a discounted jump, failure to produce adequate adjustments during the pole vault approach phase can result in serious injury (Rebella et al., 2008; Boden et al., 2012).

In this sample, individual response patterns were present within both groups. Each individual produced a unique set of results in order to satisfy their own intrinsic dynamics (Turvey, 1990). In order to investigate potential driving principles governing the behaviour of the movement system an exploratory PCA was utilised. Structural differences in the data between the regulation group and non-regulation group were identified. For the regulation group, the first three principle components were heavily loaded with variables which describe regulation of gait and velocity, two of the key task demands of the approach phase. In contrast, for the non-regulation group, only velocity based variables loaded onto PCs (Table 1). Two unique data structures were identified, one where the movement system is governed by a combination of velocity and regulatory based variables (regulation group) and one which is governed only by velocity based variables. Structural differences between the two groups were also noted as six PCs accounted for over 95% of the variance in the regulation group data while five PCs were required for the non- regulation group. Increased complexity has been linked to the prevention of the system becoming too stable and thus preventing the emergence of functional movement solutions (Davids et al., 2003). These findings advocate the need for future research to conduct a detailed analysis of the coordinative structures that emerge during the pole vault approach phase under interacting constraints (Seifert et al., 2014). Further, while ~~the influence~~ pole carriage may have an effect upon the findings of this study, it is beyond the scope of this research to understand what this influence may be. Further research, assessing the influence of pole carriage experimentally is therefore required.

The results illustrate a clear inability by some performers (non-regulation group) to achieve consistent performance outcomes, in terms of success rates, and explore reasons why these individuals cannot satisfy the regulatory task demands of the pole vault approach phase. By linking the application of biomechanics, motor control and training theory (Dick, 2007), these findings can provide coaches with meaningful information relating to the performer's approach phase performance and facilitate the development of athlete-specific training drills.

Practical solutions can be derived from a performer's approach phase data which develop the ability to functionally interact with key constraints (i.e. the task and environment) (Davids et al., 2013). In the pursuit of expert performance, degenerate behaviours (Edelman & Gally, 2001) can be explored to widen the bandwidth of variability that performers can work within while still achieving consistent performance outcomes. When implementing training drills that introduce locomotor regulation and promote functional variably during the approach phase, practitioners should manipulate key task constraints, including perception-action constraints (Davids et al., 2013), that facilitate the emergence of flexible and adaptable movement patterns. For example, for those identified as regulatory athletes, perturbing the approach phase by adjusting the starting position may prove useful. In order to still achieve the desired take-off location the athlete would be required to regulate their approach by differing amounts thus challenging their regulatory ability. In contrast, for athletes identified as non-regulatory, introducing additional perceptual information, such as a clear take-off mark on the runway, might assist in the development of regulatory abilities.

Conclusion:

Pole vaulters in this study demonstrated three distinct patterns of SD_{ff}. Locomotor regulation occurred predominantly during the penultimate and final steps. Patterns of regulation were highly individual but structural differences between those who did and those who did not regulate were identified. Regulation of locomotion was associated with an ability to produce functionally adaptable movement patterns and the consistent achievement of desired performance outcomes. These key findings can be linked to the application of training theory to allow coaching practitioners to prescribe informed interventions in the pursuit of performance enhancement. Athletes should be considered on an individual basis in order to effectively, efficiently and safely improve performance. Future work should consider the robustness of these patterns under changing task constraints.

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Figure 1. Schematic diagram showing camera positions relative to the runway. Calibration locations are defined by the crosses, black lines indicate each camera's field of view. (Not to scale).

Figure 2. Example SD_{ff} profiles for each of the regulation types as defined by Hay (1988) and Berg et al. (1994) (adapted from Needham et al., 2016). Solid line, A/D pattern. Dashed line, A/O pattern. Dotted line, R/F pattern.

Figure 3. Mean SD_{ff} profiles for regulation group (left) and non-regulation group (right) athletes with individual profiles provided in gray. Regulation group athletes presented an A/D pattern (left – solid lines) while non-regulation group presented either R/F (right – dashed line) or A/O patterns (right – dashed-dot line).

Figure 4. The relationship (R^2) between the amount of SL adjustment required and the amount of step SL adjustment produced for each group (left, regulation group & right, non- regulation group). ***** Indicates significant correlations (p <0.05).