Step characteristic interaction and asymmetry during the approach phase in long jump

Running title: Long jump and approach run rhythm

Key words: stride, run-up, step frequency, step length, sprint, velocity

Abstract

The aim of this study was to investigate the relative influence of step length and step frequency on step velocity during the approach run of high level long jumpers and to quantify the asymmetry of these step characteristics. Spatiotemporal data of the approach run were collected during national competition from 10 long jumpers (age 26.2 ± 4.1 years, height 1.84 ± 0.06 m, mass 72.77 ± 3.23 kg, personal best performance 7.96 ± 0.30 m). Analyses were conducted for total approach, early approach and late approach. For the total approach 4/10 athletes were step frequency reliant and 6/10 athletes favoured neither characteristic. At the early approach 3/10 athletes were step frequency reliant and 7/10 athletes favoured neither. During late approach 2/10 athletes demonstrated step length reliance, 7/10 athletes were step frequency reliant and 1/10 athletes favoured neither. Four athletes displayed significant asymmetry for step length and three for step frequency. However, no athletes demonstrated significant asymmetry for step velocity indicating that the asymmetrical demands of take-off do not have a marked influence on step characteristic asymmetry, probably due to the constraints of the event. Consideration should be given to the potentially conflicting demands between limbs for individual athletes.

1. Introduction

The long jump is one of the most natural, yet technically complex, events in athletics. The event involves athletes running down a runway at full speed, termed the approach run, and taking off as close as possible to the take-off line, which imposes external task constraints on performance. To be successful in the event, long jumpers need to be skilled sprinters so that they can achieve a high velocity during the approach run and be able to generate great explosive strength at takeoff. One of the key elements determining jumping distance at the event of long jump is the run-up speed developed during the approach run. Literature confirms that the relationship between horizontal velocity, take-off angle and distance jumped in long jumping is both linear and highly significant (Bridgett & Linthorne 2006; Hay 1986; Hay, Miller & Canterna 1986; Hay 1993; Lees, Graham-Smith, & Fowler, 1994; Panoutsakopoulos, Papaiakovou, Katsikas, & Kollias, 2010). Thus, the aim of the long jumper to maximize the center of mass velocity and consequently take-off angle relies on maximizing step velocity during the approach run.

Since step velocity is the product of step frequency and step length (Hay, 1994; Hunter, Marshall, & McNair, 2004; Luhtanen & Komi, 1978), it could be hypothesized that peak velocity will occur via the simultaneous maximization of both step frequency and length. However, it is well documented in studies examining sprint mechanics that a negative interaction exists between the two factors (Donati, 1995; Hunter et al., 2004; Kunz & Kaufmann, 1981; Salo, Bezodis, Batterham, & Kerwin, 2011), due to the conflicting demands associated with the increase of each. A high step frequency is preferred, but only if step length is maintained at an acceptable level. Likewise, a large step length is beneficial, but only if an acceptable step frequency is maintained (Mann, Kotmel, Herman, Johnson, & Schultz, 1984). The longer the step, the greater the ground time, but ground time must be reduced to a minimum to maximize step frequency or else over-striding occurs. Therefore, to achieve maximum sprint velocity, the optimum combination of step length and frequency must be attained and individual athletes have unique optimal combinations of step frequency and length, mainly due to anatomical differences (Donati, 1995; Kunz & Kaufmann, 1981; Salo et al., 2011).

In the case of long jump, the run-up distance leading to a jump, is defined by the rate of acceleration, the athlete's maximum speed, and the training level (Cretzmeyer, Alley, & Tipton, 1974; Sidorenko, 1985). Regardless of some differences in the rate of acceleration, it has been noted that most top jumpers reach their maximal step frequency in the last steps of the approach run. This is considered the only acceptable way in which the long jumper can strive to increase his/her approach speed and has been identified as a prerequisite for an active, powerful and fast take-off (Hay, 1986). It is of importance to note that the aim during long jump performance is not only to generate maximal speed. Whilst the long jump approach run involves athletes sprinting maximally, the skills vary slightly due to the task constraints imposed on the long jump take-off. Related research revealed that during the approach run, adjustments are made, most notably in the final strides, in order to hit accurately on the take-off board (Berg & Greer, 1995; Bradshaw & Aisbett, 2006; Glize & Laurent, 1997; Hay, 1988; Hay & Koh, 1988; Scott, Li, & Davids, 1997). This task is performed in unison with the constraints imposed by an efficient take-off, such as the increased penultimate step length and shorted final step (Hay & Nohara, 1990). Lee, Lishman and Thompson (1982) suggested that at the zeroing-in phase the optic variable ‘tau’ was coupled to the vertical impulse imparted by the athlete during the thrusting phase of the step. Kim and Turvey (1998) based on the findings of Waren, Young and Lee (1986) proposed that long jumpers probably regulate their strides by using a series of “tau gaps” (perceived time of contact to the approaching surface target) whose magnitude drives them to adjust the vertical impulse for the next series of steps. However, ground vertical impulse largely determines the vertical velocity of a step which is a prominent source of negative interaction between step length and step frequency. Hunter et al. (2004) reported that high vertical impulse had a positive effect on step length, negative on step frequency but no effect on sprint velocity. This means that long jumpers while handling the vertical impulse of the last steps so as to negotiate with the approaching target, induce interactions between the step velocity contributing factors (i.e length and frequency).

A further source of interaction between step length and frequency, 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. Asymmetry is an important consideration during running gait that has recently received attention in the biomechanics literature in sprint running (Ciacci, Michele, Fantozzi, & Merni, 2013; Exell, Irwin, Gittoes & Kerwin, 2012b). Knowledge of asymmetry during running gait can be beneficial from performance, injury and data collection perspectives (Carpes, Mota & Faria, 2010; Exell et al., 2012b; Vagenas & Hoshizaki, 1992). Due to the asymmetrical nature of the long jump take-off, and repeated explosive performance from one limb, athletes may achieve the required approach velocity through asymmetrical step characteristics, which may have implications on athlete training and injury potential. However, to the authors' knowledge, asymmetry of step characteristics has not been reported during the approach phase in jump events. Exell, Gittoes, Irwin and Kerwin (2015) reported a link between asymmetry of lower-limb strength and net ankle work performed whilst sprinting, which suggests that asymmetry could be present during the similar sprinting actions performed during the long jump approach. Bilateral asymmetry in joint torque and muscle strength is evident when long jumpers are tested (Deli et al., 2011; Kobayashi et al., 2010; Luk, Winter, O'Neill, & Thompson, 2014). This could be attributed to the task of take-off imposing a large loading to the acting lower limb (Linthorne, Baker, Douglas, Hill, & Webster, 2011; Luhtanen, & Komi, 1979; Plessa, Rousanoglou, & Boudolos, 2010; Seyfarth, Friedrichs, Wank, & Blickhan, 1999), raising issues concerning task efficiency and acute injury risks (Croisier, 2004, Deli et al., 2011). Knowing that step length improvement is mainly achieved through special strength exercises (Donati 1995; Lockie, Murphy, Schultz, Knight, & Janse de Jonge 2012), it could be suggested that bilateral asymmetry observed in muscle strength of long jumpers may further influence vertical impulse and thus step length and frequency interaction.

Besides the apparent similarities in sprinting technique between running sprints and running sprints leading to a jump and the importance of velocity on long jump performance, to the best of the authors' knowledge, no studies have ever investigated the interaction of step velocity determinants (i.e. step length and step frequency) during the full approach run of high level long jumpers where the task constraint of foot placement accuracy at take-off is also present. The aim of this study was to facilitate understanding regarding step characteristic asymmetry and the influence of step length and step frequency on step velocity in high level male long jumpers during the approach run. Subsequently, the objectives of the present study were to a) investigate the relative influence of step length and step frequency on step velocity of high level long jumpers during the full approach run and b) to quantify the direction and magnitude of asymmetry of these step characteristics. The purpose of this study was to increase knowledge and understanding of step characteristic asymmetry and interactions to inform future coaching practice.

2. Methods

2.1 Participants

The sample comprised 10 male long jumpers (mean age 26.2 ± 4.1 years, height 1.84 ± 0.06 m, mass 72.77 ± 3.23 kg) with personal best performance 7.96 ± 0.30 m. Data were collected from performances during a national athletics competition (2014 National Athletics Championship). The study was conducted in accordance with the Declaration of Helsinki for human experimentation. Informed consent was obtained by each participating athlete, as required by the Institutional Research Committee’s Guidelines for the use of human subjects.

2.2 Procedures

2.2.1 Data collection

The experimental set up followed the standard protocol applied in studies investigating visual regulation in the long jump (Bradshaw & Aisbett 2006; Hay 1988; Hay & Koh 1988, Scott, Li & Davids, 1997; Theodorou, Skordilis, Plainis, Panoutsakopoulos, & Panteli, 2013). Custom reference markers were placed at 1 m intervals parallel to the jump area approach runway's lines. The approach phase of each long jump was recorded using a high speed video camera (Casio EX F1; Casio Computer Co. Ltd., Shibuya, Japan) operating at 300 frames $\cdot$ s^{-1}. The camera was zoomed in on the athletes' feet and manually panned to allow the whole distance of each athlete's run-up to be recorded (Panteli, Theodorou, Pilianidis, & Smirniotou, 2014; Theodorou & Skordilis, 2012). The camera was positioned at the spectators' seats, at a distance of 20 m from the midline of the runway and at a height of approximately 3 m (Figure 1). The method suggested by Chow (1987) and adjusted by Hay and Koh (1988) was used for the determination of the exact touchdown distance, which was calculated with respect to the closest marker (toe-marker distance, TMD) and to the edge of the take-off board closest to the sand pit (toe-board distance, TBD). Toe-marker distance was calculated by projecting the position of the athlete's tip of their shoe at the instant of touchdown onto a line between the two near markers. Additionally, the validity of the method to determine the toe-board distance was assessed by comparing known distances with the outcome of the above described procedure using videos captured with a panned motion identical to the one of the actual recordings. This validation used test videos that recorded shoes placed on the runway at known distances (0.10 m, 1.0 m, 2.0 m, 3.0 m and every 2.0 m afterwards up to 40.0 m from the front edge of the take-off board). Toe-board distance obtained by the video-analysis was then compared with the actual toe-board distance. In all cases the mean difference between the actual and the recorded toe-board distance was ± 1 cm which was considered acceptable for the purposes of the study.

****Figure 1 near here****

2.2 Data analysis

The videos were digitised using APAS 13.3.0.3. (Ariel Dynamics, Inc., Trabuco Canyon, CA). Analysis was performed on the frames containing the instance of foot contact on the ground in each step. The analysis was performed on the approach run of the athlete’s best jump at the competition. The last two strides of the approach run were excluded from each analysis since the technical model of the event requires the last step prior to take-off being the shortest and the second to last step the longest (Hay, 1986). This pattern is necessary for the athlete to prepare for the subsequent take-off and has a direct influence on the athlete’s typical running technique and subsequently at the calculation of step velocity and frequency. Thus, the approach run of each athlete was analysed in three phases: a) the early approach (EA), containing the initial step of the approach run, up to the eleventh from the board step, b) the late approach (LA), containing the tenth to the third from the board step, and c) the total approach run, containing all steps from the initial one up to the third from the board step (Figure 2). Any walking or preparatory steps prior to the initial step were also excluded from the analysis.

****Figure 2 near here****

2.3 Step characteristics

Toe-board distance was calculated as the horizontal distance between the athlete's toe and the edge of the take-off board closest to the pit (Hay & Koh 1988). A step was defined as the time (t) and distance between two successive foot contacts (Bradshaw & Aisbett, 2006; Hay & Nohara, 1990). Time was defined as the period (in s) lapsed from one foot toe-off contact to the opposite foot toe-off contact on the ground as recorded by the panning camera. Step length was calculated by deducting two consecutive toe-board distances (Berg & Greer, 1995). The step velocity (SV) of each step was calculated according to [1]:

$$SV = \frac{SL}{t} \qquad [1]$$

Step frequency (SF) was determined by the following formula [2]:

$$SF = \frac{1}{(Tc + Tf)} \qquad [2]$$

where Tc is the contact time (in s), Tf is the flight time (in s), which was defined as the time between the end of the ground contact period of one foot to the beginning of the ground contact period of the opposite foot as recorded by the panning camera.

The accuracy concerning the identification of the time instances and the extracted step characteristics was determined through inter-researcher reliability. A second experienced experimenter independently re-examined 10% of the recorded instances of interest and conducted the analysis as described above. This procedure revealed that 57% of the recorded instances of interest were identically defined by both researchers. One frame difference was found in 36% of the cases. In only 7% of the data the difference was 2 frames. The latter difference equals to a time period of 0.006 sec, that results in an error of 1.3% concerning the calculation of step frequency. The Intraclass Correlation Coefficient (ICC) was found to be 0.9945 (with 95% confidence interval = 0.9888, 0.9974).

2.4 Statistical analysis

Since a large variation of step frequency and step length patterns exist between elite athletes and average group-level analysis could mask differences at the individual level (Salo et al., 2011), each athlete was analyzed individually. The mean and standard deviation (*SD*) of toe-board distance at each support phase as well as the mean and *SD* of step length, step frequency, and step velocity across trials were calculated with descriptive statistics for each athlete.

To investigate the reliance of each athlete on step length or frequency, a similar analysis to that presented by Salo et al. (2011) was performed. Full details are provided in the paper by Salo et al. (2011), with a brief summary included in this paper.

For each section of each approach analysed, a bootstrapping technique was employed (Matlab, R2015b) to provide 10 000 resamples of the natural log transformed step length, step frequency and step velocity values. Differences in Pearson's (r) correlations between step length-velocity and step frequency-velocity were then calculated (step frequency-velocity minus step length-velocity) for each resample. Percentile 90% confidence intervals were calculated for the correlation differences, with these values used to indicate step length or frequency reliance. Athletes were identified as being step length reliant if the mean correlation difference was positive, with the lower limit of the 90% confidence interval ≥ -0.1. Similarly, athletes were identified as step frequency reliant if they had a negative mean correlation difference, with the upper limit of the confidence interval ≤ 0.1.

2.5 Asymmetry

Individual athlete asymmetry was calculated for step characteristics based on the method presented by Exell, Gittoes, Irwin and Kerwin (2012a). The leg used by the athlete to propel from the board was defined as the preferred leg (P) while the other as the non-preferred (NP). Asymmetry values were first quantified between mean values for steps following P foot take-off (P-NP) and steps following NP foot take-off (NP-P) for each athlete using the Symmetry Angle (θ_{SYM}) method presented by Zifchock, Davis Higginson and Royer (2008). Symmetry angle values were calculated using [3]:

$$\theta_{SYM} = \frac{\left(45^{o} - \arctan\left(\frac{x_{NP}}{x_{P}}\right)\right)}{90^{o}} \times 100\% \qquad [3]$$

where θ_{SYM} is the symmetry angle, $X_{P\text{-}NP}$ is the mean value for P-NP step and $X_{NP\text{-}P}$ is the value for NP-P step. However, if:

$$\left(45^{o} - \arctan\left(\frac{x_{NP}}{x_{P}}\right)\right) > 90^{o}$$

then [3] was substituted to [4]:

$$\theta_{SYM} = \frac{\left(45^{o} - \arctan\left(\frac{x_{NP}}{x_{P}}\right) - 180^{o}\right)}{90^{o}} \times 100\% \quad [4]$$

Following tests for normality (Shapiro-Wilk), Mann-Whitney U tests were then performed between P-NP and NP-P values for each step characteristic to determine whether the asymmetry for each variable was significant ($p < 0.05$) with respect to intra-limb variability (Exell et al., 2012b).

3. Results

During the competition the participating jumpers achieved 95.0 ± 2.5% of their personal bests (Table 1). The early approach had a mean length of 16.11 ± 5.17 m, (mean number of steps: 7.40 ± 2.55), while the eight steps comprising the late approach had a mean length of 18.46 ± 0.65 m.

****Table 1 near here****

3.1. Determinants of step velocity

Correlation coefficients between each step parameter (SL and SF) and step velocity are presented in Table 2. Step length-velocity correlation magnitudes ranged from 0.06 to 0.94 whereas for step frequency, magnitudes ranged from 0.03 to 0.95. The majority of correlations were positive between step velocity and both other characteristics across all phases analyzed. However, a greater number of positive correlations were found between step length and step velocity (27/30) than between step frequency and step velocity (18/30).

****Table 2 near here****

Differences between step length-velocity and step frequency-velocity correlations, along with associated 90% confidence intervals are presented in Figures 3-5. For the overall approach (Figure 3) four athletes (#P4, #P5, #P7 and #P8) were identified as being step frequency reliant, no athletes showed step length reliance and the remaining six athletes favoured neither characteristic. At the early phase of the run-up (Figure 4), three athletes (#P4, #P5 and #P7) were step frequency reliant with no athletes demonstrating step length reliance and the remaining seven athletes being reliant on neither characteristic more than the other. At the late phase of the approach (Figure 5) two athletes (#P1 and #P7) demonstrated step length reliance, whilst seven athletes (#P2, #P4-6, #P8-10) were step frequency reliant with just one athlete (#P3) favouring neither characteristic.

****Figure 3 near here****

****Figure 4 near here****

****Figure 5 near here****

3.2. Asymmetry of step parameters

****Table 3 near here****

Four out of ten athletes exhibited significant asymmetry during their total approach run in at least one of the examined parameters between P-NP and NP-P steps (Table 3). In detail, Athlete #P5 presented a significantly higher step length on the P-NP step but a significantly higher step frequency on the NP-P step, which resulted to a higher step velocity from the NP limb (although not significant in terms of asymmetry, p = .240). Athlete #P7 also demonstrated significantly higher step length for the NP-P step and step frequency for the P-NP step, resulting in a 0.37 m/s larger mean step velocity for the NP-P step (although step velocity was again not significantly asymmetrical, p = 0.348). Athlete #P8 presented a significantly higher step length on the NP-P step, but no significant asymmetry in step frequency, which led to only a slightly higher step velocity from the NP side that was not statistically significant (p = 0.949). For Athlete #P10 step length was significantly larger for the P-NP step, whilst step frequency was significantly higher on the NP-P step; however, no significant asymmetry was reported for step velocity.

4. Discussion

The current study aimed to facilitate understanding regarding the influence of step length and step frequency on step velocity in high level male long jumpers during the overall approach run. Besides the plurality of information in the literature regarding the characteristics at the last 2 to 4 steps of the long jump run-up, the interaction of these parameters throughout the approach have been accorded much less attention with scarce data from coaching magazines only being available (Hay 1986). The analysis of the total approach revealed that four out of ten long jumpers (Athletes #P4, #P5, #P7 and #P8) were more reliant on step frequency to increase sprint velocity.

However, a holistic approach may disguise the way that step length and step frequency are manipulated by the long jumpers so as to achieve the desired horizontal velocity at the take-off board. Over the course of a sprint, step frequency and step length are characterised in most cases by high variability, with differences being evident in sprinters of all levels (Mackala 2007). Several investigators (Ae et al., 1992; Hay, 2002; Mann & Herman, 1985; Morin et al., 2012) have suggested that step frequency is the more important contributor to the velocity increases in sprint performance, while others (Brughelli, Cronin, & Chaouachi, 2011; Chatzilazaridis, Panoutsakopoulos, & Papaiakovou, 2012; Gajer, Thepaut-Mathieu, & Lehenaff, 1999; Hunter et al., 2004; Mackala, 2007; Mackala & Mero, 2013; Mero, Luhtanen, Viitasalo, & Komi, 1981; Mero & Komi, 1985; Shen, 2000) have stated that step length is a more influential variable. Furthermore, Salo *et al.* (2011) suggested that step characteristic interaction was more individualistic in elite sprint athletes, rather than a generic step characteristic that was dominant across all athletes. Research conducted so far on sprint running identifies three distinct phases for analysis: the acceleration phase, the maximum velocity phase and the speed endurance phase (Delecluse, et al., 1995). Sprint running and long jump run-up share as common the first two phases. The relative duration of each phase varies for different athletes and appears to be linked to the performance level of the athlete (Chatzilazaridis et al., 2012; Letzelter, 2006; Volkov & Lapin, 1979). While individual strategies to increase speed are variable, the overall trend to attain top speed is that sprinters will first increase step length to increase speed at submaximal levels, and then increase step frequency to achieve their highest speeds (Kuitunen, Komi & Kyröläinen, 2002; Luhtanen & Komi, 1978; Mero & Komi, 1986; Weyand, Sternlight, Bellizzi, & Wright, 2000). However, in the current study, during the initial part of the run-up only three athletes were reliant on one step characteristic over the other (#P4, #P5, and #P7), all favouring step frequency. This reliance on step frequency was adopted by more athletes during the late approach, with just two athletes (#P1 and #P7) favouring step length while seven athletes (#P2, #P4-6, #P8-10) favoured step frequency. These findings confirm the notion of Hay (1986) that an increase in stride frequency is the predominant method in which the long jumper can strive to increase his/her approach speed. During the early approach and acceleration phase of the approach run, athletes attained 95% ± 6% of mean step length and 87% ± 4% of mean step frequency compared to the late approach phase. This corresponded to 83% ± 6% of step velocity observed at late approach, which is in agreement with the speed development pattern proposed for 'the powerful type of jumpers' (Sidorenko, 1985). The remaining 17% increase in step velocity at late approach was attributed to a 5% increase in mean step length and 13% increase in mean step frequency. It seems that at higher speed (late approach) there was a smaller increment in step length and greater increment in step frequency. Exceptions may apply here to elite level athletes. Among all participants, Athlete #P1 demonstrated a high reliance on step length for developing step velocity during the total approach as well as at each separate phase of the approach. According to Gajer *et al.,* (1999) and Ito, Ishikawa, Isolehto and Komi (2006) at the highest competition level step length is the more important factor and elite athletes attain high velocities through their ability to increase step length while maintaining high step frequency. This finding is supported by the results presented for Athlete #P1 (silver medalist at the 2014 European Championship, personal best performance: 8.66 m), who is classified as an elite athlete.

Asymmetry analyses of step characteristics did not reveal a consistent trend across the athletes in this study. Four athletes (#P5, #P7, #P8 and #P10) displaying significant asymmetry for step length and three athletes (#P5, #P7 and

#P10) for step frequency with no significant asymmetry reported for step velocity. An interesting finding is that the direction of asymmetry was not related to the athletes' take-off limb, with two athletes (#P5 and #P10) displaying greater step length for the preferred limb and two (#P7 and #P8) for the non-preferred limb. These findings demonstrate fewer occurrences of significant asymmetry for step velocity but a similar number for step length and step frequency than previously reported during maximal velocity sprint running (Exell et al., 2012b), which suggests that the asymmetrical explosive nature of the take-off event may not influence step characteristic asymmetry in long jumpers. One possible explanation for this finding lies at the technical requirements of the event. Unlike in sprinting, long jumpers have to attain maximum controllable velocity and complete their run at a specific number of strides, so as to accurately hit the take-off board with the preferred leg. Successful execution of this task, which has to be performed repeatedly during a competition, is achieved only if the athlete accurately distributes (based on a pattern mastered through rigorous repetitive training) all toe contacts across the entire run up from its very beginning (Glize & Laurent, 1997). Therefore, when a long jumper presents, possibly unknowingly, positive asymmetry on one parameter of step velocity (for instance step length) this unconsciously will be offset by a respective negative asymmetry on the other parameter (step frequency) so as to maintain a balanced step velocity and accuracy of foot placements prior to take off. However, in these cases the desired velocity will be acquired with detrimental effect on running rhythm, a fact that would also explain the reliance of Athlete #P7 on step length for developing step velocity during the final phase of the approach. A finding in this study that was consistent with previous asymmetry analyses of sprint running (Exell et al., 2015) was that the athletes in the current study that demonstrated significant asymmetry for step length and frequency (#P5, #P7 and #P10) favored a different limb for each characteristic. This appears to be a fundamental characteristic of asymmetry in straight line sprint (Exell, et al., 2012b) and approach running, resulting in athletes demonstrating no significant asymmetry in step velocity.

Before concluding, we must highlight two delimitations of this study. First, the early approach phase differed among athletes in terms of absolute distance and steps. That was expected as each long jumper has a unique rhythm of developing maximum velocity. However, this may affect the generalizability of the results regarding the interaction of velocity contributors for this phase of the run-up as it may have led to larger amounts of variability within the step characteristics of each limb. Second, the data collected refer to step velocity and not to instant velocity of the center of body mass. Additional research is required to look further into the specific interaction of step length and step frequency determinants (e.g. center of mass height, angle, horizontal and vertical velocity at the instance of step touchdown, stance and take-off) on each phase of the approach.

Overall data suggest that at the acceleration phase of the approach run where submaximal speeds are attained, step frequency or step length reliance is a highly individual occurrence and individual athletes have unique optimal combinations (Donati, 1995; Kunz & Kaufmann, 1981). However, when at the late approach where high speed is attained, long jumpers increase their velocity by increasing step frequency to a greater extent than step length. Exceptions may apply here to elite level athletes. It is proposed that athletes and coaches should take this reliance into account in their training, with step frequency-reliant athletes needing to keep their neural system ready for fast leg turnover and step length-reliant athletes requiring more concentration on maintaining strength levels (Salo et al., 2011). Furthermore, consideration should be given to the potentially conflicting demands between limbs for individual athletes. Three of the ten athletes included in this study demonstrated significant asymmetry of opposing direction for both step length and step frequency, which indicates that training to improve step characteristics may need to be tailored for each limb for these athletes. However, further research is required to identify whether it would be more beneficial for athletes displaying step characteristic asymmetry to adapt their training to reduce step characteristic asymmetry or train the preferred (take-off leg) and the non-preferred (swing leg) limbs differently to take advantage of the differing step characteristic favoured for each limb. Furthermore, following the agreement with previous studies that asymmetry in step frequency and velocity appears to cancel out asymmetry in step velocity during straight line running, it would be interesting to consider this interaction during running around a curve in future research.

References

Ae., M., Ito, A., & Suzuki, M. (1992). The men’s 100 meters. Scientific Research Project at the III World Championship in Athletics, Tokyo 1991. *New Studies in Athletics*, *7*, 47-52.

Berg, W. P., & Greer, N. L. (1995). A kinematic profile of the approach run of novice long jumpers. *Journal of Applied Biomechanics*, *11*(2), 142-162.

Bridgett, L. A., & Linthorne, N. P. (2006). Changes in long jump take-off technique with increasing run-up speed. *Journal of Sports Sciences*, *24*(8), 889-897. doi: 10.1080/02640410500298040

Bradshaw, E. J., & Aisbett, B. (2006). Visual guidance during competition performance and run-through training in long jumping. *Sports Biomechanics*, *5*, 1-14. doi: 10.1080/14763141.2006.9628221

Brughelli, M., Cronin, J., & Chaouachi, A. (2011). Effects of running velocity on running kinetics and kinematics. *The Journal of Strength and Conditioning Research*, *25*(4), 933-939. doi: 10.1519/JSC.0b013e3181C64308

Carpes, F. P., Mota, C.B., & Faria, I. E. (2010). On the bilateral asymmetry during running and cycling - A review considering leg preference. *Physical Therapy in Sport*, *11*(4), 136-142. doi: http://dx.doi.org/10.1016/j.ptsp.2010.06.005

Chatzilazaridis, I., Panoutsakopoulos, V., & Papaiakovou, G. I. (2012). Stride characteristics progress in a 40-m sprinting test executed by male preadolescent, adolescent and adult athletes. *Journal Biology of Exercise*, *8*(2), 59-77. doi: 10.4127/jbe.2012.0060

Chow, J. W. (1987). Maximum speed of female high school runners. *International Journal of Sport Biomechanics*, *3*, 110-127.

Ciacci, S., Michele, R. D., Fantozzi, S., & Merni, F. (2013). Assessment of kinematic asymmetry for reduction of hamstring injury risk. *International Journal of Athletic Therapy and Training, 18*(6), 18-23.

Cretzmeyer, F. X., Alley, L. E., & Tipton, C. M. (1974). *Track and Field Athletics (8th Edition).* Saint Louis: C.V. Mosby Co.

Croisier, J. L. (2004). Muscular imbalance and acute lower extremity muscle injuries in sport: review article. *International SportMed Journal*, *5*(3), 169-176.

Delecluse, C., van Coppenolle, H., Willems, E., van Leemputte, M., Diels, R., & Goris, M. (1995). Influence of high-resistance and high-velocity training on sprint performance. *Medicine and Science in Sports and Exercise*, *27*(8), 1203-9.

Deli, C. K., Paschalis, V., Theodorou, A. A., Nikolaidis, M. G., Jamurtas, A. Z., & Koutedakis, Y. (2011). Isokinetic knee joint evaluation in track and field events. *Journal of Strength and Conditioning Research*, *25*(9), 2528-2536. doi: 10.1519/JSC.0b013e3182023a7a

Donati, A. (1995). The development of stride length and stride frequency in sprinting. *New Studies in Athletics*, *10*(1), 51-66.

Exell, T. A., Gittoes, M. J. R., Irwin. G., & Kerwin, D. G. (2012a). Gait asymmetry: Composite scores for mechanical analyses of sprint running. Journal of Biomechanics *45*(6): 1108-1111. doi: 10.1016/j.jbiomech.2012.01.007

Exell T. A., Irwin, G., Gittoes, M. J. R., & Kerwin D. G. (2012b). Implications of intra-limb variability on asymmetry analyses. *Journal of Sports Sciences, 30*(4), 403-409. doi: 10.1080/02640414.2011.647047

Exell, T. A., Gittoes, M. J. R., Irwin. G., & Kerwin, D. G. (2015). Asymmetry in sprint running: strength and performance interactions. In F. Colloud, T. Monnet, M. Domalain (Eds), *Proceedings of the 23rd International Symposium on Biomechanics in Sports* (pp. 182-185). Poitiers, France.

Gajer, B., Thepaut-Mathieu, C., & Lehenaff, D. (1999). Evolution of stride and amplitude during course of the 100 m event in athletics. *New Studies in Athletics*, *3*, 43-50.

Glize, D., & Laurent, M. (1997). Controlling locomotion during the acceleration phase in sprinting and long jumping. *Journal of Sports Sciences, 15*, 181-189. doi: 10.1080/026404197367452

Hay, J. G. (1986). The biomechanics of the long jump. In K.B. Pandolf (Ed.), *Exercise and sport sciences reviews* (pp.401-446). New York: Macmillan.

Hay, J.G. (1988). Approach strategies in the long jump. *International Journal of Sport Biomechanics, 4*, 114-129.

Hay, J.G. (1993). Citius, altius, longius (faster, higher, longer): The biomechanics of jumping for distance. *Journal of Biomechanics, 26*(Suppl. 1), 7-21.

Hay, J.G. (1994). *The Biomechanics of Sports Techniques.* 4th Ed. London: Prentice Hall International.

Hay, J. G. (2002). Cycle Rate, Length, and Speed of Progression in Human Locomotion. *Journal of Applied Biomechanics, 18*(3), 257-270.

Hay, J. G., & Koh, T. J. (1988). Evaluating the approach in the horizontal jumps. *International Journal of Sport Biomechanics, 4,* 372-392.

Hay, J. G., & Nohara, H. (1990). Techniques used by elite long jumpers in preparation for takeoff. *Journal of Biomechanics, 23*, 229-239.

Hay, J. G., Miller, J. A., & Cantera, R. W. (1986). The techniques of elite male long jumpers. *Journal of Biomechanics, 19*(10), 855-866. doi: 10.1016/0021-9290(86)90136-3

Hunter, J. P., Marshall, R. N., & McNair, P. J. (2004). Interaction of step length and step rate during sprint running. *Medicine and Science in Sports and Exercise, 36*(2), 261-71. doi: 10.1249/01.MSS.0000113664.15777.53

Ito, A., Ishikawa, M., Isolehto, J., & Komi, P. V. (2006). Changes in the step width, step length, and step frequency of the world's top sprinters during the 100 metres. *New Studies in Athletics, 21*(3), 35-9.

Kim, N. G., & Turvey, M. T. (1998). Optical flow fields and Bernstein's “modeling of the future” In M. Latash (Ed.), Progress in motor control, Vol I: Bernstein's traditions in movement studies (pp. 221-266). Champaigne, IL: Human Kinetics.

Kobayashi, Y., Kubo, J., Matsuo, A., Matsubayashi, T., Kobayashi, K., & Ishii, N. (2010). Bilateral asymmetry in joint torque during squat exercise performed by long jumpers. *The Journal of Strength and Conditioning Research*, *24*(10), 2826-2830. doi: 101519/JSC.0b013a3181c64387

Kuitunen, S., Komi, P.V., & Kyröläinen, H. (2002). Knee and ankle joint stiffness in sprint running. *Medicine and Science in Sports and Exercise, 34*(1), 166-73.

Kunz, H., & Kauffman, D. A. (1981). Biomechanical analysis of sprinting: decathletes versus champions. *British Journal of Sports Medicine, 15*(3), 177-181. doi:10.1136/bjsm.15.3.177

Lee, D. N., Lishman, J. R. & Thomson, J. A. (1982). Regulation of gait in long jumping. *Journal of Experimental Psychology: Human Perception and Performance*, 8, 448-459.

Lees, A., Graham-Smith, P., & Fowler, N. (1994). A biomechanical analysis of the last stride, touchdown, and takeoff characteristics of the men's long jump. *Journal of Applied Biomechanics, 10*(1), 61-78.

Letzelter, S. (2006). The development of velocity and acceleration in sprints: A comparison of elite and juvenile female sprinters. *New Studies in Athletics*, *21*(3), 15-22.

Linthorne, N.P., Baker, C., Douglas, M.M., Hill, G.A., & Webster, R.G. (2011). Take-off forces and impulses in the long jump. *Portuguese Journal of Sport Sciences*, *11* (Suppl. 3), 33-36.

Lockie, R.G., Murphy, A.J., Schultz, A.B., Knight, T.J., & Janse de Jonge, X.A. (2012). The effects of different speed training protocols on sprint acceleration kinematics and muscle strength and power in field sport athletes. *Journal of Strength and Conditioning Research 26*(6), 1539-1550. doi: 10.1519/JSC.0b013e318234e8a0.

Luhtanen, P., & Komi, P. V. (1978). *Mechanical factors influencing running speed*. In E. Asmussen and K. Jørgensen (Eds), *Biomechanics VI-B, International Series on Biomechanics, vol 2B*, (pp. 23-29). Baltimore, MA, University Park Press.

Luhtanen, P., & Komi, P. V. (1979). Mechanical power and segmental contribution to force impulses in long jump take-off. *European Journal of Applied Physiology and Occupational Physiology*, *41*(4), 267-274.

Luk, H. Y., Winter, C., O’Neill, E., & Thompson, B. A. (2014). Comparison of Muscle Strength Imbalance in Power lifters and Jumpers. *Journal of Strength & Conditioning Research*, *28*(1), 23-27. doi: 10.1519/JSC.0b013e3118295d311

Mackala, K. (2007). Optimisation of performance through kinematic analysis of the different phases of the 100 meters. *New Studies in Athletics*, *22*(2): 7-16.

Mackala, K., & Mero, A. (2013). A Kinematics Analysis of Three Best 100 m Performances Ever. *Journal of Human Kinetics*, *36*, 149-160, doi: 10.2478/hukin-2013-0015

Mann, R. V., Kotmel, J., Herman, B., Johnson, B., & Schultz, C. (1984). Kinematic trends in elite sprinters. In J. Terauds, K. Barthels, E. Kreighbaum, R. Mann, J. Crakes (Eds). *Proceedings of the 2nd International Symposium of Biomechanics in Sports* (pp. 17-33). Colorado Springs, USA.

Mann, R., & Herman, J. (1985). Kinematics analysis of Olympic sprint performance: men’s 200 meters. *International Journal of Sport Biomechanics*, *1,* 151-162.

Mero, A., Luhtanen, P., Viitasalo, J. T., & Komi, P. V. (1981). Relationships between the maximal running velocity, muscle fiber characteristics, force production and force relaxation of sprinters. *Scandinavian Journal of Sports Science*, *3*(1), 16-22.

Mero, A., & Komi, P. V. (1985). Effect of supramaximal velocity on biomechanical variables in sprinting. *International Journal of Sport Biomechanics 1*, 240-252.

Morin, J. B., Bourdin, M., Edouard, P., Peyrot, N., Samozino, P., & Lacour, J. R. (2012). Mechanical determinants of 100-m sprint running performance. *European Journal of Applied Physiology*, *112*(11), 3921-3930. doi: 10.1007/s00421-012-2379-8

Panoutsakopoulos, V., Papaiakovou, G. I., Katsikas, F. S., & Kollias, I. A. (2010). 3D Biomechanical Analysis of the Preparation of the Long Jump Take-Off. *New Studies in Athletics*, *25*(1), 55-68.

Panteli, F., Theodorou, A., Pilianidis, Th., & Smirniotou, A. (2014). Locomotor control in the long jump approach run in young novice athletes. *Journal of Sports Sciences*, *3*(2), 149-156. doi: 10.1080/02640414.2013.810344

Plessa, E. I., Rousanoglou, E. N., & Boudolos, K. D. (2010). Comparison of the take-off ground reaction force patterns of the pole vault and the long jump. *Journal of Sports Medicine and Physical Fitness*, *50*(4), 416-421.

Salo, A. I. T., Bezodis, I. N., Batterham, A. M., & Kerwin, D. G. (2011). Elite Sprinting: Are Athletes Individually Step Frequency or Step Length Reliant? *Medicine and Science in Sports and Exercise. 43*(6), 1055-1062. doi: 10.1249/MSS.0b013e318201f6f8

Scott, M. A., Li, F., & Davids, K. (1997). Expertise and the regulation of gait in the approach phase of the long jump. *Journal of Sports Sciences*, *15*(6), 597-605. doi: 10.1080/026404197367038

Seyfarth, A., Friedrichs, A., Wank, V., & Blickhan, R. (1999). Dynamics of the long jump. *Journal of Biomechanics*, *32*(12), 1259-1267. doi: 10.1016.S0021-9290(99)00137-2

Shen W. (2000). The effects of stride length and frequency on the speeds of elite sprinters in 100 meter dash, A kinematics analysis of three best 100 m performances ever. *Proceedings of 18th International Symposium of Biomechanics in Sports*, (pp. 333-336), Hong-Kong, China.

Sidorenko, S. (1985). The run-up in horizontal jumps. *Modern Athlete and Coach*, *23*, 41-42.

Theodorou, A., & Skordilis, E. (2012). Evaluating the approach run of class F11 visually impaired athletes in triple and long jumps. *Perceptual and Motor Skills*, *114*, 1-15. doi:10.1111/jhn.12004

Theodorou, A., Skordilis, E., Plainis, S., Panoutsakopoulos, V., & Panteli F. (2013). Influence of visual impairment level on the regulatory mechanism used during the approach phase of a long jump. *Perceptual and Motor Skills, 117*(1), 31-45. doi: 10.2466/30.24.PMS.117x11z6

Vagenas, G., & Hoshizaki, B. (1992). A multivariable analysis of lower extremity kinematic asymmetry in running. *International Journal of Sports Biomechanics*, *8*, 11-29.

Warren, W.H., Young, D.S., & Lee, D.N. (1986). Visual control of step length during running over irregular terrain. *Journal of Experimental Psychology: Human Perception and Performance*, *12,* 259-266.

Weyand, P. G., Sternlight, D. B., Bellizzi, M. J., & Wright, S. (2000). Faster top running speeds are achieved with greater ground forces not more rapid leg movements. *Journal of Applied Physiology*, *89*(5), 1991-1999.

Volkov, N. J., & Lapin, V. I. (1979). Analysis of the velocity curve in sprint running. *Medicine and Science in Sports*, *11*(4), 332-337.

Zifchock, R. A., Davis, I., Higginson, J., & Royer, T. (2008). The symmetry angle: a novel, robust method of quantifying asymmetry. *Gait and Posture*, *27*(4), 622-627. doi: 10.1016/j.gaitpost.2007.08.006

Tables

Table 1. Performance and step characteristics (mean ± *SD*). Results are presented for the total approach run up as well as being separated into early (EA) and late approach (LA).

Athlete	Best jump (m)	Approach phase	Steps (n, [m])	SL (m)	SF (Hz)	SV (m/s)
#P1	8.08	Total	20 [43.88]	2.19 ± 0.25	4.25 ± 0.28	9.38 ± 1.45
		EA	12 [24.62]	2.05 ± 0.21	4.14 ± 0.30	8.54 ± 1.30
		LA	8 [19.26]	2.40 ± 0.11	4.42 ± 0.15	10.63 ± 0.29
#P2	7.88	Total	16 [35.77]	2.23 ± 0.19	3.91 ± 0.43	8.80 ± 1.44
		EA	8 [17.02]	2.12 ± 0.21	3.61 ± 0.32	7.74 ± 1.31
		LA	8 [18.75]	2.34 ± 0.07	4.21 ± 0.30	9.85 ± 0.45
#P3	7.81	Total	14 [32.44]	2.31 ± 0.16	3.84 ± 0.31	8.95 ± 1.22
		EA	6 [12.98]	2.16 ± 0.14	3.59 ± 0.28	7.78 ± 0.89
		LA	8 [19.46]	2.43 ± 0.05	4.04 ± 0.17	9.82 ± 0.43
#P4	7.76	Total	17 [37.16]	2.18 ± 0.10	4.40 ± 0.47	9.61 ± 0.87
		EA	9 [19.63]	2.18 ± 0.13	4.15 ± 0.49	9.00 ± 0.65
		LA	8 [17.53]	2.19 ± 0.05	4.69 ± 0.23	10.29 ± 0.47
#P5	7.65	Total	14 [31.39]	2.24 ± 0.09	4.43 ± 0.36	9.91 ± 0.47
		EA	6 [13.76]	2.29 ± 0.04	4.15 ± 0.21	9.51 ± 0.44
		LA	8 [17.63]	2.20 ± 0.11	4.64 ± 0.31	10.20 ± 0.19
#P6	7.43	Total	19 [42.62]	2.24 ± 0.09	3.86 ± 0.43	8.71 ± 1.36
		EA	11 [24.07]	2.18 ± 0.20	3.61 ± 0.40	7.94 ± 1.32
		LA	8 [18.55]	2.31 ± 0.04	4.21 ± 0.14	9.76 ± 0.23
#P7	7.43	Total	14 [33.11]	2.36 ± 0.26	3.95 ± 0.51	9.26 ± 0.85
		EA	6 [14.28]	2.38 ± 0.38	3.65 ± 0.67	8.47 ± 0.65
		LA	8 [18.83]	2.35 ± 0.13	4.18 ± 0.11	9.85 ± 0.35
#P8	7.23	Total	14 [31.78]	2.27 ± 0.07	3.94 ± 0.31	8.95 ± 0.71
		EA	6 [13.59]	2.26 ± 0.92	3.65 ± 0.15	8.28 ± 0.53
		LA	8 [18.19]	2.27 ± 0.06	4.16 ± 0.21	9.46 ± 0.24
#P9	7.20	Total	14 [30.03]	2.14 ± 0.22	3.86 ± 0.56	8.33 ± 1.62
		EA	6 [12.15]	2.02 ± 0.30	3.36 ± 0.26	6.83 ± 1.30
		LA	8 [17.88]	2.23 ± 0.09	4.24 ± 0.39	9.45 ± 0.60
#P10	7.19	Total	12 [27.54]	2.29 ± 0.10	4.29 ± 0.25	9.84 ± 0.42
		EA	4 [08.99]	2.24 ± 0.12	4.17 ± 0.17	9.36 ± 0.22
		LA	8 [18.55]	2.31 ± 0.09	4.35 ± 0.27	10.08 ± 0.26

Note. SL: step length, SF: step frequency, SV: step velocity.

Table 2: Correlations for log transformed step length (SL) and step frequency (SF) with step velocity (SV) during each phase of the approach. Results are presented for the total approach run up as well as being separated into early and late approach.

	Total		**Early approach**		**Late approach**	
Athlete	**SL-SV**	**SF-SV**	**SL-SV**	**SF-SV**	**SL-SV**	**SF-SV**
1	0.80	0.95	0.82	0.93	-0.06	0.66
2	0.92	0.86	0.86	0.95	0.94	-0.55
3	0.91	0.91	0.60	0.81	0.83	0.32
4	0.92	-0.26	0.93	-0.68	0.83	0.21
5	0.89	-0.51	0.91	-0.05	0.79	-0.66
6	0.92	0.81	0.85	0.83	0.81	-0.25
7	0.70	-0.03	0.79	-0.53	-0.47	0.90
8	0.92	0.21	0.78	0.79	0.89	-0.62
9	0.89	0.71	0.61	0.91	0.94	-0.55
10	0.59	0.16	-0.14	0.54	0.81	-0.62

Table 3. Mean preferred (P) and non-preferred (NP) step characteristics for all athletes. Symmetry angle values indicates asymmetry magnitude.

Athlete	**Step Length**			**Step Frequency**			**Step Velocity**		
	P (m)	**NP (m)**	**θ_{SYM} (%)**	**P (Hz)**	**NP (Hz)**	**θ_{SYM} (%)**	**P (m/s)**	**NP (m/s)**	**θ_{SYM} (%)**
1	2.22	2.27	0.66	4.28	4.36	0.62	9.50	9.91	1.33
2	2.29	2.29	0.10	3.95	4.07	0.93	9.06	9.33	0.93
3	2.37	2.38	0.10	3.87	3.97	0.81	9.19	9.44	0.87
4	2.12	2.20	1.10	4.51	4.57	0.42	9.58	10.03	1.47
5	2.31	2.17	-1.95*	4.29	4.69	2.83*	9.90	10.16	0.84
6	2.25	2.31	0.73	3.97	3.98	0.03	8.96	9.17	0.76
7	2.20	2.40	2.73*	4.23	4.04	-1.49*	9.31	9.68	1.24
8	2.24	2.33	1.33*	4.10	3.94	-1.24	9.17	9.19	0.06
9	2.27	2.18	-1.41	3.76	4.18	3.42	8.54	9.09	1.97
10	2.41	2.23	-2.51*	4.11	4.52	3.00*	9.91	10.06	0.49

* = significant asymmetry ($p < 0.05$). Positive Sym Ang = NP > P.