DOES STEP LENGTH ADJUSTMENT DETERMINE TAKE-OFF ACCURACY AND APPROACH RUN VELOCITY IN LONG AND TRIPLE JUMPS?

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ABSTRACT

Purpose. While take-off accuracy and approach run velocity are known determinants of long and triple jump performance, the interaction of these factors with step length adjustment (SLA) is not as clear. **Methods.** The study involved 39 male and 31 female national-level long and triple jumpers. The Optojump Next device was used to analyse jump attempts. Three groups were identified according to maximum variability of footfall placement (HVF – high, MVF – medium, LVF – Low) as well as three groups regarding the onset of step length adjustment (ESLA – early, MSLA – mid, LSLA – late). **Results.** Take-off accuracy in the LVF and MVF groups was greater compared with the HVF group among females. Among males, the LVF group made significantly ($p < 0.05$) fewer foul attempts than the HVF group. The ESLA group achieved significantly ($p < 0.05$) higher velocity during the last five steps of the approach run than the LSLA group in men. **Conclusions.** Coaches should implement exercises targeting SLA in long and triple jump training exercises to improve performance.

Key words: movement pattern, gait, speed, athletics

Introduction

The long jump and triple jump are athletics events that have been part of the Olympic Games for over 100 years. At first glance, the competition task is simple: an athlete needs to jump the greatest distance possible. However, deeper analysis shows that numerous requirements need to be met in order to achieve high performance in these events with the most influential being take-off accuracy and approach run velocity [1–4].

The long and triple jumps require precise foot placement at take-off, as close as possible to the far edge of the 20-cm board from which the jump is measured. According to official regulations, only legal jumps are measured during competition, stipulating that an athlete's foot cannot exceed the distal edge of the take-off board. The delineating nature of this task is challenging to even the most experienced athletes. For example, Sebastian Bayer lost 13 cm in his best attempt in the men's long jump final during the World Championships in Daegu [5], taking 8th place, but when this lost distance (toe-to-board) was added to the official measured distance he could have won the bronze medal. Observations made during competition find that the average lost distance is quite high. For example, a lost distance of 10 cm (the highest being 24 cm) was recorded in the women's long jump final and 20 and 13 cm in the triple jump for men and women, respectively, during the World Championships in Daegu [5]. Conversely, during this competi-tion, as much as 32% of the attempts in the men's long jump final and 47% in the women's were fouled.

Despite the strong evidence on the importance of take-off accuracy for horizontal jump performance, its role in the long and triple jumps is not as well established in the literature as other factors such as approach run velocity and take-off velocity. Only a few studies [1, 6] or biomechanical investigations [5, 7] have suggested the significance of motor accuracy in the long and triple jumps. Little attention has also been devoted to the importance non-legal (foul) attempts in the long and triple jumps [6, 8]. While the results of the these studies demonstrated that the percentage of foul jumps was high in elite athletes, no research has yet sought to determine the relationship between motor accuracy, legal jump count and jumping performance.

A biomechanical research project [7] performed during the World Championships in Berlin revealed that horizontal velocity from the 11th to the 6th m and the 6th to the 1st m before take-off showed a significant ($p < 0.05$) relationship with long jump distance in men and women. Similar findings were demonstrated by Moura et al. [9], who also found a strong correlation between approach run velocity (6th–1st m before the take-off board) and the distance achieved by male athletes in the long jump ($r = 0.72$, $p < 0.001$) and triple jump ($r = 0.58$, $p < 0.05$). Other researchers indicated a significant positive correlation ($r = 0.42$, $p < 0.05$) between final step velocity and jumping performance in elite European long jumpers [10]. However, other studies found weak positive correlations or even none between approach run velocity and jump distance [2, 3]. Possible inferences for this result may lie in the non-linear coupling between speed

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and jumping performance in the long and triple jumps. Such an explanation was proposed by Bridgett and Linthorne [4], who showed non-linear relation between approach run velocity and jump distance in elite male long jumpers.

Based on observations of experienced athletes, various studies [1, 11, 12] have determined that the approach run consists of an acceleration and zeroing-in phase. They posited that an athlete focuses on reaching maximal speed using a consistent foot placement pattern during the first phase and then adjusts step length to arrive at the take-off board with the highest accuracy during the second phase. This observation was based on analysis of footfall variability throughout the approach run, finding that footfall variability increased gradually (acceleration phase) and subsequently systematically decreased (zeroing-in phase). It is widely believed that athletes use a visual control strategy to regulate footfall placement in the zeroing-in phase at approximately four or five steps before the take-off board [11, 12]. However, inter-individual analysis revealed that the starting point of step length adjustment was highly varied in elite athletes [1], where Larry Myricks started the zeroing-in phase from the fifth to last step (jumping 8.25 m), Carl Lewis from the fourth to last step (8.63 m) and Mike Powell from the second to last step (7.98 m).

The large body of research on long and triple jump performance have treated step length adjustment as a general singularity [11–13]. There are limited data on the relationship between step length adjustment and approach run velocity and take-off accuracy, particularly in elite athletes [1, 8, 14]. Based on the findings of the aforementioned studies, it could be inferred that (1) less variability in footfall placement during step length adjustment may allow for greater take-off accuracy and (2) early onset of step length adjustment may provide greater gains in approach run velocity and take-off accuracy than later step length adjustment. However, these hypotheses are based on research with various limitations (e.g. small sample sizes or limited datasets). Therefore, the purpose of this study was to further elucidate the interaction of step length adjustment with approach run velocity and take-off accuracy in a sample of highly skilled long and triple jumpers.

Material and methods

All research procedures were approved by the university's institutional review board. Long and triple jumpers participating in seven athletic competitions (four indoor and three outdoor), including the Polish Championships, First Class League Competitions and Polish Athletics Association national meets, were observed and analysed. Athletes selected for study inclusion must have performed at least five attempts during a given competition in which the full jump sequence was completed and set an official distance (OD) greater than 7.25 m for the men's and 5.65 m for women's long jump and 15.00 m for men's and 12.50 m for the women's triple jump, both at a wind velocity below 1 m·s⁻¹. The final sample consisted of 17 male long jumpers (mean OD = 7.51 m), 22 male triple jumpers (mean OD = 15.67 m), 19 female long jumpers (mean OD = 5.96 m) and 12 female triple jumpers (mean OD = 13.02 m).

The Optojump Next (Microgate, Italy) was used to analyse the jumping attempts. This system consists of 25 pairs of 1-m measurement bars aligned parallel to one another on an approach runway that transmit a solid infrared light beam via light-emitting diodes (1.04 cm resolution) positioned 0.2 cm above the ground. The system detects any interruptions in communication between the bars at an accuracy of 1 ms. This device was used to measure contact time as the time course from initial foot touchdown to take-off (with the same foot) and flight time as the time course from foot take-off to touchdown on the opposite foot. Step length was determined as the distance from the tip of the spike shoe at take-off to the tip of the opposite leg's shoe at take-off while mean step velocity was calculated as the ratio between step length and the sum of contact time of the take-off leg and flight time during this step. A pilot study assessed the test–retest reliability of selected variables, finding high intra-class correlation coefficients in the range of 0.90–0.96.

To determine step length adjustment (SLA), footfall variability was measured in the final ten steps. Toe-to-board distance for each foot strike was measured and then the standard deviation (SD) of the toe-to-board distances for each analogous step of the approach run across each jump attempt was taken to calculate footfall variability. The onset of SLA was identified as the point when SD_{max} of toe-to-board systematically decreased until take-off [14]. Both legal and foul jumps were included in analysis. The analysis considered following dependent variables: maximum variability of footfall placement, onset of SLA, take-off accuracy (as the sum of the toe-to-board distances at take-off without regard to the direction of error divided by the number of attempts), final step velocity, mean velocity during the five final steps, and the number of foul jumps and jumps performed behind the board.

K-means cluster analysis was conducted twice to identify groups based on SD_{max} for football variability and again according to the onset point of SLA, separately for males and females. The data were log transformed in order to improve the normality assumption ($p < 0.05$). One-way ANOVA was used to determine if there were any significant differences between defined groups for each measure. Tukey's honestly significant difference test was used for post-hoc analysis to conduct pairwise comparison between groups. An alpha level of 0.05 was set for all statistical procedures. All data are reported as means ± SD.

Results

Cluster analysis identified the existence of three groups according to the SD_{max} of toe-to-board distance, females with high ($n = 9$), medium ($n = 13$) and low ($n = 9$) footfall variability and also males with high ($n = 13$), medium ($n = 17$) and low ($n = 9$) footfall variability. Cluster analysis additionally revealed three groups with regards to the onset of SLA: females with early SLA ($n = 11$), mid SLA ($n = 11$) and late SLA ($n = 9$) and males with early SLA ($n = 15$), medium SLA ($n = 13$) and late SLA ($n = 11$).

Table 1 presents the accuracy and velocity variables across the cluster-derived female groups for maximum footfall variability, $F(2, 28) = 46.96$, $p < 0.001$. The results of ANOVA revealed differences in take-off accuracy, $F(2, 28) = 7.37$, $p < 0.01$, with post-hoc analysis showing that the HFV group was less accurate compared to the female athletes from the LFV and MFV groups.

Table 2 shows the results of the accuracy and velocity variables across the males differentiated by maximum footfall variability, $F(2,36) = 112.58$, $p < 0.001$. A significant between-group difference was found in the amount of foul jumps, $F(2,36) = 4.45$, $p < 0.05$, with post-hoc analysis indicating that the HFV group had a larger number of foul attempts than the LFV group.

Table 3 provides the accuracy and velocity variables among the female groups extracted based on onset of SLA, $F(2, 28) = 57.33$, $p < 0.001$, with no significant differences observed between the groups.

Table 4 presents the accuracy and velocity variables among the groups of males according to the onset of SLA, $F(2, 36) = 125.46$, $p < 0.001$. Significant main effects were observed for velocity at the last step, $F(2, 36) = 7.59$, $p < 0.05$, and the mean velocity of the final five steps, $F(2, 36) = 7.22$, $p < 0.05$. In both cases, the ESLA group achieved higher velocities than the MSLA and LSLA groups.

Discussion

The purpose of this study was to examine the relationships between step length adjustment and the determinants of long and triple jump performance. It needs to be highlighted that this study was conducted during actual competition, which may facilitate better understanding of the factors determining competitive success.

Consistent with the predictions of previous studies [1], we found associations between maximum footfall variability during the approach run with take-off accuracy in female athletes with low or medium footfall variability. In turn, low footfall variability during the approach run was associated with a low rate of foul jump attempts in male athletes. One other important finding was that earlier step length adjustment positively influenced approach run velocity in male athletes while showing a positive trend in female athletes.

Our findings can lead to the conclusion that lower footfall variability is associated with improved take-off accuracy than higher footfall variability in female athletes. These observations are in agreement with the idea that a high level of movement variability is often associated with lower motor performance [15]. It is probable that inflated footfall variability in the acceleration phase

Table 1. Accuracy and velocity variables across the females grouped by maximum footfall variability

Footfall variability group	Maximum footfall variability (SD_{max})	Take-off accuracy (m)	Number of foul attempts (n)	Number of attempts behind the board (n)	Velocity at last step (m · s⁻¹)	Mean velocity of last five steps (m · s⁻¹)
LFV	15.14 ± 2.74#¥	0.10 ± 0.03#	1.7 ± 1.2	0.8 ± 1.0	9.41 ± 0.80	8.19 ± 0.36
MFV	23.26 ± 1.90#	0.12 ± 0.06#	1.3 ± 1.1	1.0 ± 1.5	9.51 ± 0.42	8.41 ± 0.25
HFV	43.71 ± 11.60	0.23 ± 0.14	1.6 ± 1.3	1.8 ± 1.2	9.56 ± 0.32	8.43 ± 0.16

LFV – low footfall variability, MFV – medium footfall variability, HFV – high footfall variability;
\# – significantly different from HFV ($p < 0.05$), ¥ – significantly different from MFV ($p < 0.05$)

Table 2. Accuracy and velocity variables across the males grouped by maximum footfall variability

Footfall variability group	Maximum footfall variability (SD_{max})	Take-off accuracy (m)	Number of foul attempts (n)	Number of attempts behind the board (n)	Velocity at last step (m · s⁻¹)	Mean velocity of last five steps (m · s⁻¹)
LFV	18.74 ± 3.10#¥	0.08 ± 0.03	0.9 ± 0.8#	0.3 ± 0.7	10.98 ± 0.63	9.55 ± 0.34
MFV	30.07 ± 3.47#	0.10 ± 0.05	1.3 ± 1.1	0.7 ± 1.4	11.02 ± 0.62	9.65 ± 0.38
HFV	42.04 ± 4.44	0.12 ± 0.07	2.3 ± 1.5	0.9 ± 1.8	10.85 ± 0.57	9.62 ± 0.37

LFV – low footfall variability, MFV – medium footfall variability, HFV – high footfall variability;
\# – significantly different from HFV ($p < 0.05$), ¥ – significantly different from MFV ($p < 0.05$)

resulted in exaggerated step length adjustment in the zeroing-in phase due to the limited amount of time and distance available for effective step length adjustment. Conversely, it is probable that the female athletes who displayed lower footfall variability had more automated gait regulation during the entire approach run and for this reason may have been able to direct greater attention on take-off accuracy. The consistent reproduction of a movement pattern is particularly important in tasks involving closed motor skills in order to aid task performance [15]. This highlight the importance of using check marks in the approach run to instil a repeatable gait pattern during training and competition.

On the one hand, our results suggest that too high footfall variability may hinder take-off accuracy. On the other hand, we did not find differences in take-off accuracy between female athletes who displayed medium and low footfall variability during the approach run. In the light of Hay's [1] suggestions, this may indicate the existence of individual footfall variability among national class long and triple jumpers. This assumption is confirmed by the male athletes' results in the current study, where we found no dependency between footfall variability with take-off accuracy. The differences in movement pattern variability in elite athletes has been observed in prior studies. It is worth nothing that Hay [1] even suggested footfall variability norms for elite athletes, where 0.20 m or less was considered excellent and 0.25 m or greater mediocre. However, Hay and Koh [6] found that athletes displaying low footfall variability as well as higher variability showed a high magnitude of take-off accuracy. In turn, Schöellhorn and Bauer [16] reported that in-

ternational athletes exhibited a higher level of inter-individual variation in comparison with national athletes. A number of researchers [1, 6, 12] have suggested that athletes should not strive to produce consistent jumping movement patterns, but rather improve the skills behind step length adjustment. Maraj et al. [17] believe that a consistent movement pattern is more of a determinant of take-off precision (i.e. same point on the runway, not necessarily from the take-off board) and not take-off accuracy. In turn, Scott et al. [12] found that a similar amount of footfall variability in the last step did not translate into a similar level of take-off accuracy in elite athletes and non-long jumpers. Interestingly, the values of take-off accuracy in non-long jumpers from the previously mentioned studies were close to the values of the female jumpers who showed the highest footfall variability in the present study, while take-off accuracy of the other groups from this study was similar to take-off accuracy of elite athletes of Hay's study [1].

As previously indicated, foot placement accuracy is crucial not only for horizontal jump performance but also in light of the fact that foul jumps are not counted in competition. The present study provides valuable data in this area, in which we observed that the lowest amount of footfall variability was associated with a significantly lower number of foul jumps compared with highest amount of footfall variability in male athletes. In addition, our results demonstrated that the male and female athletes with the lowest footfall variabilities achieved three to two fewer jumps behind the edge of the take-off board, respectively, than their cohorts from

Table 3. Accuracy and velocity variables across the females grouped by the onset of step length adjustment

Step length adjustment group	Onset of step length adjustment (n supports)	Take-off accuracy (m)	Number of foul attempts (n)	Number of attempts behind the board (n)	Velocity at last step (m · s^{-1})	Mean velocity of last five steps (m · s^{-1})
ESLA	6.6 ± 1.8#¥	0.14 ± 0.08	1.3 ± 1.5	1.2 ± 0.9	9.64 ± 0.45	8.51 ± 0.22
MSLA	3.4 ± 1.2#	0.13 ± 0.05	1.7 ± 1.1	1.2 ± 1.5	9.35 ± 0.33	8.23 ± 0.22
LSLA	1.2 ± 0.4	0.17 ± 0.11	1.7 ± 1.0	1.4 ± 1.2	9.46 ± 0.59	8.33 ± 0.33

ESLA – early step length adjustment, MSLA – mid step length adjustment, LSLA – late step length adjustment;
– significantly different from LSLA ($p < 0.05$), ¥ – significantly different from MSLA ($p < 0.05$)

Table 4. Accuracy and velocity variables across the males grouped by the onset of step length adjustment

Step length adjustment group	Onset of step length adjustment (n supports)	Take-off accuracy (m)	Number of foul attempts (n)	Number of attempts behind the board (n)	Velocity at last step (m · s^{-1})	Mean velocity of last five steps (m · s^{-1})
ESLA	7.5 ± 1.1#¥	0.08 ± 0.03	1.8 ± 1.5	0.3 ± 0.2	11.35 ± 0.34#¥	9.90 ± 0.23#¥
MSLA	4.1 ± 1.0#	0.11 ± 0.06	1.0 ± 1.2	0.9 ± 1.5	10.81 ± 0.67	9.54 ± 0.44
LSLA	1.8 ± 0.4	0.10 ± 0.03	1.4 ± 1.2	0.5 ± 1.3	10.72 ± 0.50	9.37 ± 0.43

ESLA – early step length adjustment, MSLA – medium step length adjustment, LSLA – late step length adjustment;
– significantly different from LSLA ($p < 0.05$), ¥ – significantly different from MSLA ($p < 0.05$)

the other groups. Although these differences were not statistically significant, when we consider the findings en bloc, the hypothesis that high footfall variability may perturb jumping performance during competition appears sound. The plausible explanation for this observation is that elite athletes during competition focus on attaining the highest distance by maintaining or increasing running velocity rather than focusing on absolute take-off accuracy. Support for this assumption is provided by the findings of Maraj [18], who demonstrated that the greatest number of foul jumps occurred when athletes were instructed to concentrate on jumping as far as possible compared to neutral conditions where no instruction was provided or when the athlete was required to be as accurate as possible. Future research should examine this issue in greater detail. Based on the present results it appears that the pattern of footfall variability (e.g. ascending–descending vs. non-fluent) needs to be further explored within the context of take-off accuracy.

Finally, we did not find any relation between footfall variability with approach run and take-off velocities. Data and conclusions in this field are limited as they are based on inter-individual analysis only. Hay and Koh [6] reported that athletes with small and high footfall variability maintained similar velocities in the last step. This may indicate that other characteristics of step length adjustment may affect horizontal jumps velocity, such as the onset of step length adjustment, which is further elucidated below.

In analysing the influence of the onset of step length adjustment, it appeared that early step length adjustment produced greater velocity during the final steps of the approach run than middle and late step length adjustment in the male athletes. We also discovered a clear trend (although non-statistically significant, $p = 0.07$) among the female athletes in this regard. This is in line with previous research, such as by Bradshaw and Aisbet [14], who found that early step length adjustment was associated with a consistent step pattern in the zeroing-in phase, suggesting this may contribute to higher approach run velocity. Furthermore, they found that earlier gait regulation also resulted in improved jump performance in elite athletes. Interestingly, the benefits of early step length adjustment on take-off velocity as well as performance were also revealed in other disciplines, for instance gymnastics [19]. Bradshaw and Aisbet went on the describe an alternate situation when the jumper delays step adjustment to a later phase of the approach run, in effect leaving little margin for additional manoeuvring (steering). In this case, the probability of deceleration increases, particularly if the gait adjustment involves only the final two to three steps. This may be the result of increased task complexity when step adjustment is executed much later in the approach run due to less time afforded for take-off preparation [14]. However, it is worth highlighting that there is no evidence sup-

porting the notion that approach run velocity changes at the moment of the onset of step length adjustment. Galloway and Connor [19] analysed this issue by comparing three elite long jumpers. Their results showed that at least one athlete accelerated after the starting point of step length adjustment was reached, while the approach run velocity of the others was maintained. Future studies should address this issue by involving a greater samples of athletes. An additional noteworthy observation from the present study was that the approach run and take-off velocities were the greatest when the male athletes adjusted their step at approximately 6.5 steps (7.5 supports) from the take-off, whereas previous studies suggested athletes should regulate their steps at five steps before the take-off [1, 20].

No significant differences were found between the groups with early, mid and late step length adjustment groups with regard to take-off accuracy or the number of foul jumps. This is in contrast with the study by Omura et al. [8], who revealed that the late onset of step length adjustment was associated with fewer foul attempts in a sample of national-level male athletes. We believe that an explanation for such a difference may be caused by the speed–accuracy trade-off [21]. It is probable that there are additional take-off accuracy mechanisms regulating horizontal jump performance independent of the onset of step length adjustment and approach run velocity in elite athletes.

Limitations

The present investigation contains a number of limitations that need mention. First, our data were collected over the course of seven separate competitions, where different regulatory (e.g. indoor vs. outdoor conditions) and non-regulatory (motivation and coach instructions) factors may have influenced the results [22]. Maraj et al. [18] concluded that a greater number of fouls occur when athletes focus on maximizing jump distance and that horizontal velocity decreases when athletes were instructed to attain greater take-off accuracy. However, it was not possible to control these factors under competitive conditions. Second, this study integrated both long and triple jump attempts in one dataset, although it is possible that these tasks do not share the same gait pattern.

Conclusions

The results of the present investigation suggest that exercises directed at the improvement of step length adjustment skill should be considered by coaches of long and triple jumpers. In the case of poor take-off accuracy (either by fouling or jumping behind the board), training should focus on exercises that promote step length consistency or rhythm drills. To enhance approach run velocity, the onset of step length adjustment needs to be evaluated and modified is late onset is found so as to stimulate earlier step regulation.

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