Influence of Visual Impairment Level on the Regulatory Mechanism Used in the Long Jump

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ABSTRACT

The purpose of the study was to investigate how visually impaired long jumpers regulate their strides during the approach and adjust the technique of the final strides to prepare for the take-off. The attempts of 35 visually impaired class F11, F12 and F13 long jumpers at the 2009 International Blind Sports Association European Championships in Rhodes, Greece, were analysed. No significant differences (p>.05) were observed among the jumpers of different classes concerning velocity, stride frequency and stride length in the last steps of the approach. Analysis revealed that visually impaired athletes are able to perceive time-to-contact to the take-off area and act in a regulatory manner. Additionally, angle of takeoff increased as the visual impairment increased. Finally, a more rapid knee flexion of the take-off leg was observed for F13 jumpers (p<.05), resulting in a larger maximum knee flexion (p<.05) during the taken off. It is possible that factors such as the size and surface properties of the take-off area used in F12 and F13 competitions contribute to these differences.

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Introduction

Success in the long jump is primarily determined by the effectiveness of the approach phase, which in turn profoundly depends on the consistency of its length, number of strides and pattern of speed development[1]. The clear significance of the approach upon performance has made the event popular among researchers exploring the relation between perception and action[2].

In addition to the dominating factor of approach velocity, an important performance demand is the accuracy of leg plant on the take-off board[3]. In order to minimise their toe-to board distance (S_{TTB}), long jumpers regulate their stride length in the final four or five strides of the approach[3-10]. This regulation is accomplished using visual information that feeds a continuous control based on a perception-action coupling[2]. In order to conduct the desired regulation, the majority of long jumpers seek to acquire the necessary visual information by directing their gaze towards the take-off board during the final three strides[11]. The time-to-contact estimation of the athlete approaching the take-off board is dominated by the ***tau*** hypothesis, which proposes that a quantity (tau) present in the visual stimulus provides the necessary information[12].

The regulation of the final strides consists of the adjustment of the body segment configuration in order to prepare for the take-off, with the technical execution of the last strides prior to take-off representing a significant factor in the official distance (S_{OFF})[13-15]. The greatest amount of stride length adjustments caused by visual regulation has been found to be in the final two strides of the approach[2,7]. This coincides with the elongation of the penultimate stride length compared to the previous ones, a technique element characterised as "longer penultimate – shorter last stride"[16]. The adoption of this technique in the final part of the approach causes the body centre of mass (BCM) to drop in the penultimate stride[17]. This BCM lowering creates the circumstances for developing higher vertical take-off BCM velocity without demanding an extensive reduction of horizontal BCM velocity during the push-off from the take-off board[18]. Additionally, this technique contributes to the greater BCM vertical displacement[19]. However, the visual trail is not present in all athletes.

The long jump is an event in para-sport competitions, including the Paralympic Games, and from 1976 visually impaired jumpers have competed in three categories determined by the level of visual impairment (F11 - no vision; F12 - visual acuity: 2/60; F13 - visual acuity: 6/60)[20], defined by associated changes in visual acuity and/or visual field[21].

Visual acuity describes the ability of the eye to perceive detail and is usually measured using a chart, which contains letters changing progressively in size. In SNELLENS's[22] notation, visual acuity is defined as the distance at which the patient can recognise a letter, divided by the distance at which a person with normal eyesight can do this. Thus, a visually impaired long jumper with a Snellen visual acuity of 6/60 can hardly see at a distance of six metres (approximately 3 strides from the board) an object that a non-visually impaired would be able to see at 60m. On the other hand, visual field refers to the ability to detect objects in the periphery of the visual environment. The normal forward-facing binocular field of vision is about 210°and 90° in the horizontal and vertical plane, respectively. Visual field loss will manifest itself in an inability to detect peripheral objects and, often, in a reduced ability to avoid obstacles.

Athletes participating in Class F11 have no light perception in either eye, or have visual acuity poorer than 2/60[20,23]. During competition, F11 athletes must wear approved opaque glasses blocking out any light. The visual acuity of a Class F12 athlete should range between 2/60 and 6/60, and/or his/her visual field should be constricted to a diameter of less than 5°[20,23]. Class F13 athletes have a visual acuity ranging from 2/60 to 6/60 and/or a restricted visual field diameter of less than

40°[20,23]. Class F13 long jump athletes compete under the IAAF[24] competition rules as athletes with normal eyesight[20], using a standard take-off board, i.e. a 0.20m x 1.22m white rectangle. For the F11 and F12 classes a larger, white chalked take-off area (1.00m x 1.22m) is used and competitors may also use a caller (usually the coach) to provide acoustic feedback during the approach run[23]. As for S_{OFF}, despite the lesser visual aquity, the European records in class F12 are greater by 2% in males and 12% in females compared to class F13.

Research conducted in class F11 jumpers revealed that blind athletes adopt a similar regulation pattern up to the final four to five strides of the approach[25]. Additionally, class F11 triple jumpers exhibit a regulation pattern during the approach that is similar to the one observed in sighted athletes but initiated on the third rather than the fifth-last stride[25]. The authors advocated that the acoustic sensory input provided by the coach probably allows class F11 athletes to perceive time to arrival to the proximal take-off board and act by regulating their strides. This observation suggests that visual information may not dominate the control mechanism of regulation for these athletes. It is also reported that visually impaired F13 Athletes improved S_{OFF} after a period of feedback training[26]. The researchers found that the jumpers developed a better kinesthetic model that led to S_{OFF} improvements, as indicated by the minimised loss of speed in their approach to the take-off.

However, no relevant study was found in the literature addressing the issue of how visually impaired long jumpers adjust the technique of the final strides in order to prepare for the take-off. The purpose of the study was to investigate: i) if the control mechanism of stride regulation in the approach phase of long jump is present in class F11, F12 and F13 athletes, ii) if the control mechanism of regulation emerges on a different stride in class F11, F12 and F13 athletes, and iii) if the biomechanical parameters of the long jump take-off are different in class F11, F12 and F13.

It was hypothesised that modifications will occur in different classes of visually impaired long jumpers when executing the approach, especially the last strides and the take-off, taking into consideration that they experience the acquisition of different visual information during the approach. Furthermore, the comparison of the biomechanical parameters of the final strides of the approach and the take-off in class F11, F12 and F13 long jumpers could provide additional information concerning the contradicting phenomena of F12 achieving greater jumping distances.

The uniqueness of the present study was that the biomechanical parameters of the last strides and the take-off were examined for visually impaired long jumpers during competition, thus supplementing the findings concerning this issue in the literature and providing information to practitioners working in the field of visually impaired athletics.

Methods

Participants

Four class F11 (all males, 31.3 ± 5.1years, 1.80 ± 0.04m, 75.8 ± 2.9kg), 19 class F12 (13 males and 6 females; 25.9 ± 6.4years, 1.71 ± 0.04m, 73.7 ± 5.5kg) and 12 class F13 (4 males and 8 females; 24.8 ± 6.4years, 1.74 ± 0.05m, 74.5 ± 4.7kg) long jumpers were recorded during their participation in the 2009 International Blind Sports Association (IBSA) European Championships in Rhodes, Greece. The participants were included in the study because of their official classification as F11, F12 and F13 class athletes by the IBSA and the International Paralympic Committee (IPC) medical boards and the confidence that the respective athletes comprised a group representative of top European visually impaired long jumpers. The research was conducted after the provision of permission by the IBSA and in accordance to the Institutional Research Ethics Code.

Instrumentation and Procedures

All participants performed six trials each. Each trial was recorded but the foul attempts were excluded from the analysis. The inclusion of a participant in the analysis had to meet the presupposition criteria of the execution of at least five legal jumps. In total, 136 legal approaches were included in the analysis (*n* = 22, *n* = 59 and *n* = 55 from four F11, ten F12 and ten F13 jumpers, respectively). As for the biomechanical analysis, the best valid jump for each examined athlete was selected for the kinematical analysis (*n* = 35).

Stride regulation: A panning digital video camera (SONY HDR-SR10, Sony Electronics, Inc.), operating at 50 fps, was fixed on a tripod positioned on the stands at a distance of 15m from the midline of the approach lane and at a height of 3m from ground level (Figure 1). The camera was manually panned and it was zoomed in on the athletes' feet for recording each participant's entire approach. For the execution of the panned analysis, 0.05m x 0.05m custom reference markers were placed on either side of the lines defining the runway, and formed one-meter zones along the entire runway. The calibration of the field of view and the panning procedure was conducted following the instructions proposed by GERVAIS et al[27]. The camera positioning allowed all markers to be visible on the captured motion of interest. In the authors' opinion, the experimental set-up for data collection did not disturb the athletes' effort throughout the event. The frames of each foot touchdown on the ground were extracted from the selected video recordings. The method suggested by CHOW[28] and adjusted by HAY & KOH[8] 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 proximity to the pit edge of the take-off area (toe-board distance, TBD). TMD was calculated by projecting the position of the athlete's shoe toe at the instant of touchdown onto a line between the two near markers through a digitisation process using the APAS/Wizard 13.3.0.3 software (Ariel Dynamics Inc., Trabuco Canyon, CA). TBD was then calculated by the addition of the TMD and the marker-board distance. This procedure was repeated for every footfall in all the analysed approaches.

Biomechanical analysis of the take-off: A 2D-DLT kinematical analysis method[29] was utilised. A stationary Casio EX-FX1 (Casio Computer Co. Ltd, Shibuya, Japan) digital video camera was set to a sampling frequency of 300 fps (Figure 1). The camera was fixed on a rigid tripod that was placed at a height of 1.2m and a distance of 3.7m before the take-off line and 14m from the middle of the runway. The camera was placed perpendicular to the plane of motion and recorded the right-sided view of the last three strides of the approach (3L: third-to-last, 2L: penultimate, and 1L: last stride, respectively) and the take-off from the board (BO). The calibration of the recorded

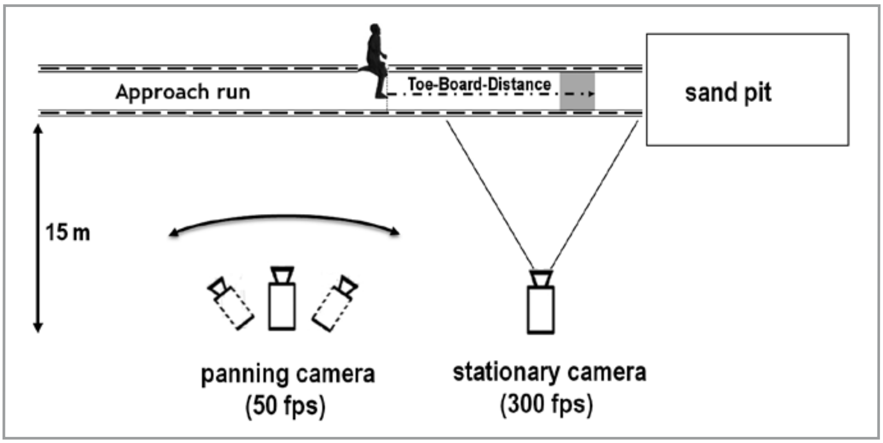

Figure 1: Set up of the experimental procedure

view was accomplished by placing four 0.02m x 2.0m poles at several predefined spots at the middle of the runway and within the filming view in order to produce two-dimensional coordinates. The X-axis represented the direction of the runway and Y-axis was vertical and perpendicular to the X-axis. The video files were processed with the Adobe Premiere Pro 2.0 software (Adobe Systems Incorporated, San Jose, CA) in order to extract the video-fields. Twenty-two anatomical points of the body (tip of the toe, 5th metatarsal, heel, ankle, knee, hip, shoulder, elbow, wrist and 5th metacarpal on both sides of the body, 7th cervical vertebra and the top of the head) were manually digitised in each field using the KAPA-MOTION v.15 (Kapa-Invent, Orsay, France) software. The coordinates of the BCM were calculated for every field using the anatomical data provided from Dempster[30]. A 2nd order low-pass Butterworth filter with a cut-off frequency ranging from 6.2 to 11.2Hz, based on the noise calculated with residual analysis[31], was selected for smoothing.

Accuracy of the analyses

In order to assess the error of the panning recording, the four last footfalls of the athletes' approaches were recorded with a stationary digital CASIO EX-FX1 (Casio Computer Co. Ltd, Shibuya, Japan) video-camera (sampling frequency: 300fps). The camera was elevated 1.2m from the ground and fixed on a rigid tripod, which was positioned 12m from the midline of the approach lane and 1.0m before the beginning of the take-off area. The optical axis of the camera was perpendicular to the plane of motion. The recorded area was calibrated by consecutively placing a 2.5m x 2.5m frame with 16 reference markers. The athlete's toes at every support phase were manually digitised using the APAS/Wizard 13.3.0.3 software (Ariel Dynamics Inc., Trabuco Canyon, CA). The extracted coordinates of the athlete's toe at the instant of touchdown were then compared to the TBD obtained from the panning analysis. Differences concerning the TBD extracted from both analyses were found to be negligible (0-0.5%). Additionally, the validity of the method to determine the TBD was assessed by comparing the outcome of the above-described procedure using videos captured with a panned motion identical to the one of the actual recordings. These test videos recorded shoes placed on the runway at known distances (0.10m, 1.0m, 2.0m, 3.0m and every 2.0m afterwards up to 25.0m from the front edge of the take-off board). TBD obtained by the video-analysis was then compared with the actual TBD, which revealed an error of ± 1%, an error within range of those found in similar studies[5,8-10]. Based on these findings, the data from the panning recordings were used for the assessment of the parameters used in this study. As for the last strides and take-off 2D analysis, the accuracy of the 2D reconstruction was determined by Root Mean Square error, after randomly re-digitizing 1% of the captured frames. An error of 0.4cm and 0.3cm was found for the X- and Y-axis, respectively.

Examined parameters

In order to identify the regulatory incidence and make appraisals with what literature reports for its occurrence[3,4,7-10], the inter-trial analysis was used. This analysis takes into account the variability of TBD for a given stride across all trials. Foot placement variability for a particular stride was expressed by the standard deviation of TBD (TBD_{SD}) for each footfall of a participant across all of his/her trials[8,9,32]. The point where stride regulation appeared was defined as the footfall at which the maximum value of TBD_{SD} (TBD_{SDmax}) was recorded, providing that it represented the peak of an ascending trend followed by an immediate descending trend[32]. The accuracy of targeting the take-off area was reflected by the TBD_{SD} of the footfall in the take-off area (TBD_{SDto}). For better comprehension, the point at which stride regulation commenced was also expressed as the distance from the take-off line.

The percentage distribution of adjustment ($ADJ_{\%}$) in each one of the regulated strides was calculated for each participant following the method suggested by HAY[7] with the means computed as (equation 1):

(1) $$ADJ_{\%} = \frac{(TBD_{SDi} - TBD_{SDi-1})}{(TBD_{SD\max} - TBD_{SDto})} \times 100$$

where i is the i^{th}-last contact.

The instant of touchdown (TD) was defined as the first field where the foot had clearly contacted the ground. The instant of take-off (TO) was defined at the first field where the foot had clearly left the ground. Thus, contact (t_C) and flight (t_{FL}) time could be extracted for each stride. The braking phase at the take-off board was defined as the period from touchdown to the board to the maximum flexion of the support leg's knee joint, while from that instant to the take-off was assumed as the propulsive phase[33].

Furthermore, the following biomechanical parameters were calculated based on the XY coordinates extracted for the digitised anatomical points:

- Stride frequency (SF): the number of strides taken per second.
- Stride length (S): the horizontal distance between the touchdown points of the feet recorded for two consecutive supports.
- Touchdown distance (S_{TD}): the horizontal distance of the toes of the support foot to BCM projection at the instant of touchdown.
- Take-off distance (S_{TO}): the horizontal distance of the toes of the support foot to the BCM projection at the instant of take-off.
- Horizontal BCM velocity (Vx): the first-time derivative of the horizontal BCM displacement.
- Vertical BCM velocity (Vy): the first-time derivative of the vertical BCM displacement.
- Angle of take-off (AngPr): the arc-tangent of the ratio of the vertical to the horizontal BCM velocity at the instant of take-off.
- Horizontal ankle touchdown velocity (V_ATD): the horizontal velocity of the ankle at the instant of touchdown.
- BCM height (H_{BCM}): the height of the BCM at the instants of touchdown (H_{TD}), of its maximum lowering during the support phase (H_{AM}) and toe-off (H_{TO}).
- Support leg knee joint angle: the angle formed between the thigh and the shank at the instants of touchdown (θk_{TD}), of its maximum flexion (θk_{MF}) and take-off (k_{TO}). The magnitude of the joint's flexion (θk_{FLEX}) and extension (θk_{EXT}) during the support phases was also calculated.
- Swing leg knee joint angle: the angle formed between the thigh and the shank at the instants of take-off (θk_{SW}).
- Knee joint angular velocity: the maximum value of the angular velocity of the support leg's knee joint during the support, where positive values expressing the extension (ωk_{EXT}) and negative values the flexion of the joint (ωk_{FLEX}).
- Thigh inclination (φ_{TH}): angle formed by the horizontal axis and the thigh of the swing leg at the instant of take-off.
- Torso inclination: the angle between the horizontal level and the line connecting the midpoints of the hips and shoulder joints' axis at the instant of touchdown (φ_{TRS}TD) and take-off (φ_{TRS}TO).
- Mechanical Work: the mechanical work done at the braking (W_{BR}) and the propulsive (W_{PR}) phase expressed per kg of body mass computed as proposed by LEES et al[33].

Statistical analysis

Data are expressed as mean ± standard deviation. The groups were checked for normal distribution (Kolmogorof-Smirnof test, $p > 0.05$) and equality of variance (Levene's test, $p > 0.05$). The differences in the biomechanical parameters among the groups of different level of visual imperaiment were examined with one way ANOVA with Schefe post hoc test. Pearson corralation was adopted to examine the relationship between S_{OFF} and selected biomechanical parameters. All statistical proceedures were conducted using the SPSS 10.0.1 software (SPSS Inc., Chicago, Il). The level of significance was set at $p = 0.05$ for statistical tests.

Results

Despite the fact of longer S_{OFF} in F12, no significant difference ($p > .05$) was observed between the examined groups (5.76 ± 0.23m, 6.07 ± 0.58m and 5.75 ± 0.79m for F11, F12 and F13, respectively).

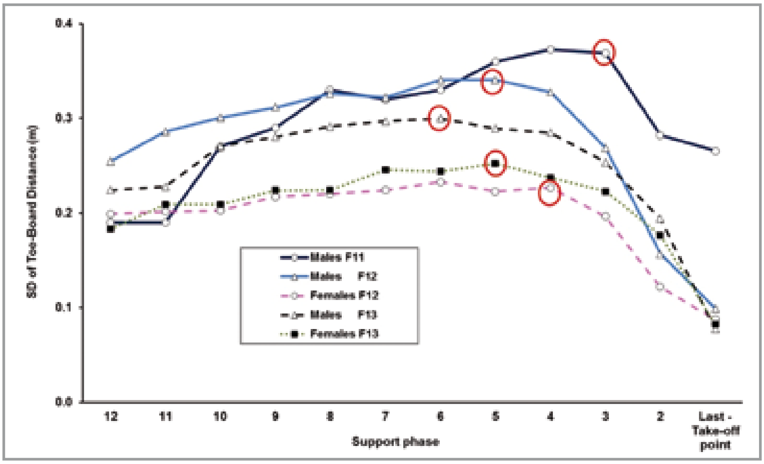

Figure 2: Trend of TBD_{SD} for the examined long jumpers at each support phase (The red circles indicate the support phase that mean maximum TBD_{SD} value occurs before an acute decline is recorded (onset of regulation). The coach mark could be placed at this support phase, indicating the end of the non-regulated part of the approach run.)

Toe-board-distance variability

The analysis of the pattern of footfall variability in each participant revealed that the TBD_{SD} presented a systematic ascending - descending trend and thus regulation for the vast majority of the examined jumpers (Figure 2). In detail:

Class F11: Regulation was observed for three out of four athletes. Those three athletes reached a ***mean*** maximum TBD_{SD} value of 0.36m (± 0.14) at a ***mean*** distance of 6.00m (± 1.00) and as an average on the 3rd support phase from the take-off area (two athletes on the 4th and one athlete on the 3rd). Following that point, an acute decline in footfall variability (onset of regulation) commenced and the ***mean*** TBD_{SD} was finally reduced at take-off to a TBD_{SDto} of 0.29m (± 0.05)

Class F12: Analysis revealed that the TBD_{SD} presented a systematic ascending - descending trend for all athletes, male and female. The male athletes reached a ***mean*** maximum TBD_{SD} value of 0.341m (± 0.057) at a ***mean*** distance of 9.09m (± 0.26) and as an average on the 5th support phase from the take-off area (two athletes on the 6th and three athletes on the 5th). Likewise females reached a ***mean*** maximum TBD_{SD} value of 0.226m (± 0.685) at a ***mean*** distance of distance of 6.28m (± 0.26) and as an average on the 4th support phase from the take-off area (one subject on the 5th and four athletes on the 4th). Subsequently, an acute decline commenced (onset of regulation) and the ***mean*** TBD_{SD} was finally reduced at take-off to a ***mean*** TBD_{SDto} of 0.09m (± 0.049) and 0.08m (± 0.014) for males and females respectively.

Class F13: Male athletes reached a ***mean*** maximum TBD_{SD} value of 0.30m (± 0.19) at a ***mean*** distance of 10.84m (± 0.29) and as an average on the 6th support phase from the take-off board (one athlete on the 7th, two on the 6th and one on the 5th). Female athletes also demonstrated the same trend and reached a maximum ***mean*** TBD_{SD} of 0.25m (± 0.14) at a ***mean*** distance of 8.24m (± 0.55) on the 5th support phase from the take-off board (three athletes on the 6th, two on the 5th and one on the 4th). Following this point, an acute descending trend (onset of regulation) was recorded for the remaining steps until the ***mean*** TBD_{SD} was finally reduced to 0.07m (± 0.06) and 0.08m (± 0.02) for males and females, respectively.

Table 1: Percentage of athletes commencing regulation at the final strides of the approach (between and within the groups of participants)

Stride	6th last	5th last	4th last	3rd last	2nd last
Class F13 (n = 10)	10%	50%	30%	10%	
males (n = 4)	25%	50%	25%		
females (n = 6)		50%	33%	17%	
Class F12 (n = 10)		20%	40%	40%	
males (n = 5)		40%	60%		
females (n = 5)			20%	80%	
Class F11 (n = 3, males)*				67%	33%

**NOTE: no evident onset of regulation for one F11 jumper.*

The distribution of the onset of regulation between and within the groups of participants is presented in Table 1. The majority of jumpers initiated regulation between the 5th and 3rd to last support phase of the approach run.

Distribution of adjustments

The $ADJ_{\%}$ for all the participants in all groups is presented in Table 2. A trend to adjust later during the final steps of the approach was revealed for female F12 and F13 jumpers compared to male athletes within the same classes.

Biomechanics of the last strides of the approach

The outcome of the comparison among groups concerning the approach parameters is presented in Table 3. No significant differences (p > .05) were observed concerning Vx, SF and S. The maximum horizontal BCM velocity at the final three strides of the approach was significantly correlated with S_{OFF} (r = .929 , p < .001). Additionally, no significant differences (*p* > .05) were detected for the examined part of the approach phase concerning the alterations of H_{BCM} at the instances examined. An average H_{BCM} lowering of 0.04 ± 0.02m was recorded during the flight phase of 2L. In general, ankle and knee angular kinematics were not different between groups (*p* > .05). However, a more detailed look revealed that F11 had significantly (*p* < .05) more flexed qk_{TD} at the penultimate stride compared to F13 (137.3° ± 6.9, 140.3° ± 3.7 and 145.0° ± 6.1 for F11, F12 and F13, respectively). Also, a tendency observed for F11 and F12 for a more rapid knee flexion during the support phase of the last stride as compared to F13. Finally, a significant (*p* < .05) difference was noted at the support phase of 1L concerning V_ATD (1.39 ± 0.60 m/sec, 2.03 ± 0.95 m/sec and 1.63 ± 0.54 m/sec for F11, F12 and F13, respectively).

Table 2: Percentage distribution of adjustment made for all participants

Stride	4th last stride	3rd last stride	2nd last stride	Last stride
F11 Males (n=3)*			65%	72%
F12 Males (n=5)	23%	26%	44%	22%
F12 Females (n=5)	12%	16%	42%	23%
F13 Males (n=4)	10%	20%	26%	41%
F13 Females (n=6)	6%	17%	21%	54%

**NOTE: no evident onset of regulation for one F11 jumper.*

*Table 3: Comparison of the biomechanical parameters of the approach between the examined class F12 and F13 long jumpers (**mean ± standard deviation**)*

Parameter	F11 (*n*=4)			F12 (*n*=19)			F13 (*n*=12)		
S3L (m)	1.91	±	0.24	1.95	±	0.16	1.89	±	0.15
S2L (m)	2.14	±	0.30	2.12	±	0.22	2.00	±	0.17
S1L (m)	1.82	±	0.15	1.88	±	0.09	1.82	±	0.22
SF3L (Hz)	3.98	±	0.20	4.23	±	0.30	4.17	±	0.31
SF2L (Hz)	3.82	±	0.56	4.18	±	0.44	4.07	±	0.41
SF1L (Hz)	4.67	±	0.18	4.72	±	0.34	4.81	±	0.41
Vx2L (m/sec)	8.19	±	0.21	8.82	±	0.60	8.37	±	0.90
Vx1L (m/sec)	7.79	±	0.20	8.41	±	0.48	8.23	±	0.62
VxMAX (m/sec)	8.36	±	0.28	8.96	±	0.61	8.49	±	0.79

Table 4: Comparison of the biomechanical parameters of the take-off phase between the examined class F12 and F13 long jumpers (mean ± standard deviation)

Parameter	F11 (*n*=4)			F12 (*n*=19)			F13 (*n*=12)		
S_{TTB} (m)	0.61	±	0.18	0.28	±	0.19[a]	0.09	±	0.09[a,b]
t_CBO (sec)	0.154	±	0.015	0.140	±	0.015	0.141	±	0.016
S_{TD} (m)	-0.62	±	0.08	-0.60	±	0.09	-0.62	±	0.06
U_ATD (m/sec)	3.23	±	1.19	2.68	±	0.59	2.68	±	0.95
VxTD (m/sec)	7.69	±	0.35	8.20	±	0.51	7.85	±	0.71
VxTO (m/sec)	6.16	±	0.10	6.90	±	0.53	6.54	±	0.67
ΔVxBO (m/sec)	-1.53	±	0.45	-1.30	±	0.46	-1.31	±	0.44
VyTD (m/sec)	-0.04	±	0.20	-0.05	±	0.23	-0.20	±	0.26
VyTO (m/sec)	2.93	±	0.13	2.81	±	0.35	2.40	±	0.46[a,b]
ΔVyBO (m/sec)	2.97	±	0.28	2.86	±	0.42	2.60	±	0.46
S_{TO} (m)	0.34	±	0.08	0.35	±	0.06	0.35	±	0.07
AngPr (°)	25.0	±	4.0	21.7	±	2.8	19.9	±	3.4[a]
ϑk_{TD} (deg)	159.75	±	3.50	158.47	±	5.45	162.50	±	7.49
ϑk_{FLEX} (deg)	-18.13	±	8.49	-18.23	±	5.39	-25.18	±	5.89[b]
ϑk_{TO} (deg)	176.00	±	2.00	173.18	±	3.56	170.75	±	7.49
φ_{TH} (deg)	-6.88	±	5.72	-2.35	±	7.66	-2.44	±	8.54
φ_{TRS}TD (deg)	91.80	±	2.16	93.08	±	5.63	93.48	±	4.68
φ_{TRS}TO (deg)	90.20	±	5.50	90.46	±	7.32	92.67	±	6.50
ωk_{FLEX} (rad/sec)	-6.78	±	2.37	-7.36	±	1.55	-10.16	±	3.62[a,b]
ωk_{EXT} (rad/sec)	9.45	±	3.82	9.91	±	1.74	9.69	±	1.34
W_{BR} (J/kg)	-5.61	±	1.52	-6.22	±	3.02	-5.76	±	3.09
W_{PR} (J/kg)	3.22	±	5.79	2.45	±	4.19	1.11	±	3.32

NOTE: [a]: $p < .05$ vs. F11, [b]: $p < .05$ vs. F12

Biomechanics of the take-off

Table 4 presents the parameters of the take-off phase. F11 had a slightly longer t_CBO than the other examined classes. F12 had an almost three-fold S_{TTB} compared to F13, but half the S_{TTB} recorded for F11 ($p < .05$). F13 had the lowest VyTO than the other to classes ($p < .05$). Additionally, results revealed that AngPr increased as the visual impairment increased (significant difference observed between F11 and F13). Finally, a more rapid knee flexion was observed for F13 compared to the other groups ($p < .05$), that resulted in a mentionable larger a larger θk_{MF} ($p < .05$) during the push off. No statisticaly significant differences ($p > .05$) were noted in the rest of the examined parameters.

Discussion

The first aim of the current study was to identify the presence of a regulatory mechanism in athletes with different levels of visual impairment (as defined by the IPC[23]) in the long jump. The present findings were consistent with those reported in the literature and support the hypothesis that regulation is present irrespective of the amount of visual deprivation. Two segments could be identified during the approach phase for all participants. In the first segment, the toe-board distance variability was gradually increased until it reached a peak value. Following this peak, a second segment commenced and variability was markedly decreased as the take-off area was approached. This descent in variability, according to the literature[3-5,7,8,10] denotes the perception of the board primarily through activation of visual processes (optical *tau*), which supplies the crucial information to the control mechanism to calculate the time to contact. The similarity of the amount of variability to what has been reported in sighted athletes of various levels of expertise[5,7-10] is not surprising and confirms the findings of THEODOROU & SKORDILIS[25] who reported TBD_{SDmax} values of 0.38m for class F11 triple jumpers. These data confirm the first hypothesis of the study and demonstrate that visually impaired athletes, although severely deprived of the "dominant" optical *tau*, are able to perceive time-to-contact to the take-off area and act in a regulatory manner.

Furthermore, as hypothesised, not all the groups initiated regulation on the same instant. In class F12 athletes, the process of perceiving the error and acting for its rectification commenced one (in males) or two (in females) strides later compared to previous reports for sighted athletes[4,7,8,10,32,34]. Class F13 athletes on the other hand performed regulation with the descending pattern of variability commencing approximately on the fifth (males) and fourth (females) stride before the take-off board. For all groups, the bulk proportion of the adjustment was spread over the last two strides (see Table 1). This was comparable with the pattern observed also in athletes without visual impairment (67%[7]; 79%[3]). Class F12 participants however seemed to perform most of the adjustment on the second rather on the last stride compared to class F13. This process could be attributed to the fact that in class F12 the board is considerably wider and the length of the jump is measured from the point of take-off and not from the board's proximal edge to the pit, thus allowing a constrain-free placement of the take-off foot.

The accuracy of the take-off stride constitutes a constraint indicative of spatial perception both for sighted athletes and athletes with visual impairment. Class F13 long jumpers demonstrated a precision of foot placement on the board comparable with non-visually impaired athletes. The *SD* of toe-board distance recorded for the take-off stride for class F13 and F12 long jumpers resembled that recorded for elite level athletes[7,8] and was considerably superior to novice long jumpers (0.15m[3]) and non-long jumpers (0.25m[10]).

It is evident in Table 2 that all the participating athletes in this study regulated the final portion of the approach run, since 90% of class F13 athletes commenced regulation on the 4^{th} to last stride or earlier as opposed to

60% of class F12 long jumpers. Construing these findings, aside from the observation that class F11 jumpers commence their regulation on the second or third to last stride, it is hinted that the onset of regulation is deescalating as the level of visual impairment increases. The source of this variation must be down to the level of visual impairment escalating from class F13 to class F11. Nevertheless, within each group not all athletes commenced regulation on the same stride. Variations across athletes and gender for the onset of regulation have been reported both for non-visually impaired[7] and class F11[25] athletes. One possible source of this variation in the present study may be the magnitude of visual impairment for each athlete within a visual impairment class. A class F12 or F13 athlete with visual acuity of 6/60, for example, may have better estimation of the location of the board compared to a counter athlete with a 3x reduced visual acuity of 2/60.

Moreover, reduced visual acuity coupled with visual field defects could have a major impact on mobility and orientation since vision provides feedback on the location of targets with respect to the body and assists in calibrating subsequent body movements[35,36]. Two forward-facing class F13 long jumpers with similar levels of visual acuity but different amount of visual field defect, especially in the vertical plane, will have equal ability to perceive the distance from the board but may differ in their sensitivity to detect it as they are approaching, which is expected to affect the pattern of regulation of their strides. However, since the examination and classification of the athletes is performed exclusively by the medical boards of the IPC[23], any information regarding the exact level of visual acuity and visual field is not disclosed so as to allow further examine this issue.

Another probable source of variation at the onset of regulation could also be the origin of visual impairment or any previous visual experiences. Literature suggests that there is a difference between adults with acquired and congenital deprivation of vision in the way they monitor the location of objects as well as their locomotion, balance and postural control[37-39]. However, this parameter is neither scanned nor constitutes a classification criterion for the IBSA or IPC and the athletes' classification is based on their current status of visual impairment and not on its cause. According to SHERRILL[40], classification constitutes an essential feature in disability sports ensuring that winning or losing depends on training, skill, motivation, fitness, talent, and not on unevenness among the competitors or a variety of disability related variables. The range of disability must be small to ensure that most athletes are eligible to hold viable competition within each class and that athletes with the greatest defects would not be unduly disadvantaged when compared to athletes with lower defect levels[41].

Generally, it was assumed that the examined athletes constituted a homogeneous group and were classified by the IPC's medical boards in the particular classes taking into account that athletes within a group are not disproportionately advantaged or disadvantaged in comparison to each other. This poses a limitation in the study, but the variations observed in some competitors regarding the onset of regulation could be used to investigate the even-handedness of the classification system used and future studies should look into this issue.

As for the biomechanics of the last strides and the take-off, the following can be discussed. The results of the present study concerning the parameters of the final three strides of the approach were in reasonable agreement with those reported for visually impaired long jumpers participating in recent Paralympics[42]. S_{OFF} was considerably shorter even when compared to sub-elite European performers[14,43]. It is worth noting that despite the fact of their lesser visual acuity, class F12 athletes achieved an approximately 10% longer S_{OFF} than class F13 jumpers. Nevertheless, S_{OFF} differences between class F12 and F13 were in agreement with the trend referring to the respective European IBSA long jump records. With the horizontal velocity attained at the last stages of the approach being the single most important factor concerning long jump performance[13], it seems reasonable that class F12 jumped further since they were marginally faster at the final strides. However, V_ATD at the support phase of the last stride was different among groups, indicating a dissimilarity concerning the muscle actions for the preparation of take-off.

During the final stages of their approach, the examined athletes used the "longer penultimate – shorter last stride" technique, a technique that is similarly adopted by sighted long jumpers as an effective manner to lower H_{BCM} prior to the take-off[14-18,44]. This finding could be attributed to the fact that the examined jumpers were experienced since they were systematically trained. It has been suggested that long-term systematic training allows visually impaired athletes to become independent of visual inputs and to achieve technique efficiency comparable to sighted athletes[45].

Analysis showed that all groups had a slightly negative Vy at touchdown for take-off, which has been suggested to be beneficial for the jump[17,46]. The combination of low H_{BCM} and fast Vx of the approach aids in placing the take-off leg well ahead of the body and in the avoidance of its extensive flexion, factors believed to contribute in the development of large Vy during the take-off phase[47]. An extended knee at the touchdown on the board is thought to be supplemental to the above factors[46,48]. Since the maximum Vx of the approach was marginally non-significantly different and almost equal values between groups were observed concerning S_{TD}, V_ATD, H_{TD}, and θk_{TD} at the take-off board, the longer S_{OFF} of class F12 jumpers could be attributed to their larger take-off Vy developed as a result of the significantly smaller θk_{FLEX}. Parameters such as Vy comprise the vertical component of the long jumping take-off, with its optimal changes from touchdown to take-off thought to be a discriminating factor for maximum jumping range[49], suggesting this component to be essential for better results especially in female competitors [50,51].

The ωk_{EXT} and ωk_{FLEX} recorded at the take-off phase were within range of previous findings[48]. Nevertheless, class F13 jumpers flexed their take-off leg's knee with a significantly larger angular velocity that resulted in the smaller θk_{FLEX} than the other classes. This might indicate the inability of the examined class F13 athletes to apply enough resistance to prevent the excessive knee flexion, since it is believed that an enlarged θk_{FLEX} is related with weaker lower limb muscles and reduced leg spring force[33,48]. This is of importance since lower leg stiffness has found to be important concerning the achievement of S_{OFF}[52]. It is worth mentioning that the take-off for class F13 is executed on a more rigid surface (the take-off board) compared to class F11 and F12 (chalked area on the rubber surface of the approach runway). This could be a factor that has an impact upon the parameters discussed above.

Finally, the mechanical work found in the present study was within reasonable agreement with studies of sighted athletes[33]. It is interesting that vertical jumping performance was shown to be unaffected from the level of visual acuity in both trained and untrained visually impaired individuals[53] and that it is not different between visually impaired and sighted persons[54,55]. Based on the above, the force and power production capability of visually impaired long jumpers is an issue that should be further examined.

The limited number of long jump participants for class F11 and the uneven distribution of males and females in class F12 and F13 at the studied event did not allow the comparison among the groups without excluding the possible existence of a gender effect. However, an inter-group preliminary descriptive analysis of the data revealed that the trends of females and males was consistent with the differences observed between class F12 and F13 athletes as an entity, thus considering the results of the comparison of the examined groups as valid.

Conclusions and Recommendations

The main finding of the study was that stride regulation is a process present in sighted as well as in visually impaired class F11, F12 and F13 long jumpers. The control mechanism of regulation has shown to be evident earlier in non-visually impaired jumpers compared to the examined athletes. This signifies the importance of visual perception in the regulatory stimuli.

The biomechanical analysis of the last strides of the approach for visually impaired long jumpers provided information concerning the technique utilised and the differences caused by the different level of visual acuity. A similar pattern concerning the execution of the final two strides of the approach was evident for the examined classes. However, class F12 jumpers were differentiated concerning the support leg's motion during the last support and the vertical component parameters in the take-off phase. It seems that the width, the surface properties and the colour of the take-off area might be supportive for the differences concerning the examined groups. Furthermore, the force application capabilities of visually impaired long jumpers during the impulse for the take-off is an issue that should be further examined. In addition, the possibility of the existence of auditory regulation/guidance provided to class F12 jumpers by their caller should be also addressed in future studies.

It would have seemed reasonable that visually impaired athletes executed the long jump technique differently than sighted athletes because of their limited visual acuity and thus their supposed inability to regulate their final strides of the approach in order to optimise their take-off parameters. The present study provides evidence that the biomechanics of technique adopted by visually impaired long jumpers was proportionately similar to those described for sighted athletes. Thus, useful information that is needed for implementing adequate training stimuli is available from the present study for coaches and practitioners concerning the biomechanics of the final stage of the approach of visually impaired long jumpers.

Finally, our recommendations are that 1) future research should focus on the nature of the sensory inputs employed by visually impaired athletes during the final portion of the approach run and the manner in which they manipulate spatio-temporal parameters (velocity, ground contact times, and stride flight times) and 2) the width, surface properties and colour[56] of the take-off area should be appropriate for long jumpers with visual impairment.

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