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Inter-Limb Asymmetry in the Kinematic Parameters of the Long Jump Approach Run in Female Paralympic-Level Class T63/T64 Athletes

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Abstract: The purpose of this study was to evaluate the inter-limb asymmetry in the kinematic parameters of the approach run in elite-level female Class T63/T64 long jumpers and its relationship to performance. Three Class T63 and nine Class T64 female long jumpers were examined during a competition. The temporal and kinematic parameters of their approach steps (step length: SL; step frequency: SF; average step velocity: SV) were measured using a panning video method and speed radar. The symmetry angle was the measure of inter-limb asymmetry. The results revealed that SF and SV were significantly ($p < 0.05$) larger in the intact lower limb. Significant ($p < 0.05$) asymmetry was revealed for SL, SF, and SV in 2/12, 3/12, and 1/12 jumpers, respectively. The direction of asymmetry for SF was towards the leg wearing the prosthesis for all examined jumpers. The official jump distance was significantly ($p < 0.05$) positively correlated with the maximum velocity attained during the approach and negatively correlated with the symmetry angle for SF. It is concluded that the observed asymmetry in SF was compensated for by the modifications observed in the SL that consequently resulted in no asymmetry in SV, leading the participants to effectively utilize their approach speed optimally in terms of long jump performance.

Keywords: paralympics; track and field; sport performance; lower limb prosthesis; inter-limb asymmetry; laterality; biomechanical analysis; step kinematics

1. Introduction

Increased interest in Paralympic sports is evident in recent years, as revealed by the increasing attendance of both participants and spectators of Paralympic sports events. Despite this increased interest, limited scientific evidence exists concerning sports prostheses and performance [1].

Among the events that have attracted the interest of researchers is the Paralympic long jump. This is due to the fact that performance is mostly defined by approach speed [2], but, at the same time, this has to be balanced with perception abilities in the form of perception–action coupling, which is necessary to mark a valid jump [3,4]. Thus, the execution of the approach run is crucial for the optimization of long jump performance. The optimization of the take-off is related to the attainment of a large-as-possible near-maximum controlled speed during the approach run, which is accomplished with the consistent development pattern of step length (SL) and velocity (SV) during the approach [5]. This is a demanding task due to the existence of considerable variability in the execution of the steps during the early approach run [6] which increases importance of the regulation of SL in the last five steps [7]. This factor is affected by sex, with female long jumpers presenting a greater variability in SL and SV than male jumpers [8]. In addition, a considerable inter-limb asymmetry in SL in the late approach was previously found in female long jumpers [9].

During the late approach, an additional task is to prepare for the transformation of the kinetic energy into dynamic energy during the take-off [10]. This transformation is more efficient if the length of the penultimate step is larger than all the proceeding steps and is followed by a smaller-than-the-penultimate final step [5]. This pattern is generally acknowledged as the "larger penultimate—shorter last step" technique that allows for the initiation of the take-off with favorable conditions for the development of vertical velocity [11]. During the take-off, a considerable amount of loading is imposed on the lower limb that is used as the take-off leg, due to the applied vertical ground reaction forces [12]. As this considerable load is applied only to the take-off leg, the long jump is generally characterized as an asymmetrical sports activity because of the unilateral execution of the take-off [13].

Inter-limb asymmetry, namely the absence of lateral equality in a given factor between body segments, i.e., their force application capability, is a research topic that is becoming increasingly popular among scholars. Systematic long-term sports training is considered to be related to limb dominance, which can be observed as an adaptation to improve performance [14]. This dominance could lead to asymmetries since the dominant limb is submitted to large loading for an extensive time period [15]. Although debated [16], past research has suggested that a 10% inter-limb asymmetry in force–output could result in lower sport [17] and vertical jump performance [18]. Furthermore, past research has proposed that an inter-limb asymmetry of 10–15% and above could be connected to musculoskeletal injury [19]. There are a number of calculation methods and indices used to estimate inter-limb asymmetry [16,20]. Among them, symmetry angle (θ_{SYM}) is considered a robust method to document asymmetry-related parameters (i.e., the magnitude and the direction of asymmetry) without considering, in the calculation, the existence of a reference limb that poses a limitation in the asymmetry estimation [16,20]. When the θ_{SYM} method is used, the right-side value is plotted against the respective left-side value, forming an angle with regard to the *x*-axis [21]. When a 45° angle is created, symmetry is considered to be evident [21].

Past research has provided evidence for the existence of a relationship between inter-limb asymmetry and injury in track and field long jumpers [22–24], since larger inter-limb asymmetry was found in track and field jumpers compared to athletes with a bilateral pattern of sport movement [25]. However, there is bias in the literature, as no significant differences were revealed in terms of force parameters between the take-off and the swing leg in athletes competing in athletics jumping events [13,26]. When examining the event per se, namely the execution of the long jump approach, significant inter-limb asymmetry in step frequency (SF) and SL was reported in a considerable number of able-bodied jumpers [6]. When considering the long jump approach executed by Paralympic unilateral lower limb amputee athletes, where the use of a prosthesis is required, it is unknown whether the inter-limb asymmetry in the approach run's step parameters is increased or balanced due to the beneficial effect of the mechanical properties of the prosthesis [27,28], as, so far, this is not clear in the literature. Nevertheless, it is evident that Paralympic jumpers were more frequently injured than other track and field athletes [29].

In clinical setups, prostheses are useful for the acquisition of a high level of inter-limb symmetry of gait biomechanical parameters [30]. On the other hand, running using prostheses resulted in higher inter-limb asymmetry in trans-femoral amputee Paralympic athletes [31]. This increase is attributed to the differences in ground reaction forces applied between the intact and the prosthetic limb [32]. With regard to unilateral lower limb amputees, two classes are acknowledged by World Para-Athletics and by the International Paralympic Committee (IPC) [33]: Class T63, where competitors are "athletes with single through knee or above knee limb deficiency competing with a prosthesis", and Class T64, where competitors are "athletes with unilateral below knee limb deficiency competing with a prosthesis" [33]. It is suggested that increased inter-limb asymmetry exists in lower limb amputees, with asymmetry being related to the proximity level of the amputation [34–36]. Nevertheless, past research has examined the biomechanical parameters of elite-level long jumpers with transtibial and transfemoral amputation [37–45], as well as with upper arm amputation [46]. As found in past research on the long jump performed by lower-limb amputees, below-knee amputees execute the technical elements of the event similarly to able-bodied long jumpers [39,43]. However, this was not confirmed for above-knee amputees of both sexes [39–41].

As mentioned above, the attainment of a high approach velocity and the lack of inter-limb asymmetry in the approach step kinematics are crucial for the optimization of long jump performance. However, in the case of Class T63/64 long jumpers, the effect of the use of the prosthesis is not known, as stiffness and force application are different between limbs in sprinting activities [32,47,48]. To the best of the authors' knowledge, there is limited research evidence concerning the effect of prostheses on the asymmetry of long jump approach step parameters. One previous study examined a very small number (n = 3) of female jumpers [44]. Research conducted in competition suggested that able-bodied female long jumpers exhibited significant asymmetry in SL rather than SF in a greater percentage than male jumpers [6]. In addition, sex differences in approach speed have been reported in Class T63/T64 long jumpers [49]. Thus, it is of interest to examine whether elite female Class T63/T64 long jumpers present inter-limb differences in the step characteristics of the long jump approach run. The aim of the present study was to evaluate kinematic asymmetry during the approach run in elite-level female Class T63/T64 long jumpers during competition and its relationship with performance. It was hypothesized that significant asymmetries will be observed in SL, SF, and SV and that these asymmetries will be related to decreased performance.

2. Materials and Methods

2.1. Participants

The approach run of the women's long jump event formerly named T42/44 (contemporary Class T63: n = 3 jumpers and Class T64: n = 9 jumpers) in the 2012 London Paralympics was analyzed. The convenience sample was examined based on the official classification of current Class T63/64 athletes by the IPC medical boards, the assumption that the Paralympic sample comprised of athletes that reflect a group of elite long jumpers, and the approval of the International Paralympic Committee to conduct the investigation. The study was conducted according to the recommendations of the Declaration of Helsinki. Ethical approval was acquired from the Institutional Ethics Committee (IRB00003099).

2.2. Data Acquisition

The approach lane was calibrated using custom 5 × 5 cm reference markers. These markers were attached to the track surface at both sides of the runway's lines, creating 1.00 × 1.30 m reference zones [13]. Every competition attempt of the participants was recorded with a high-speed digital camera (Exilim-Pro-EX-F1, Casio Computer Co. Ltd., Shibuya, Japan; sampling rate: 300 fps; resolution: 512 × 384 pixels). The camera was attached to a stable tripod located in the spectators' seating area. The tripod was positioned 15 m from the mid-line of the runway, approximately 3 m above the track height, and was placed 2 m from the take-off board. The camera was manually panned to record the last 12 steps of the approach, with the field of view zoomed in on the athletes.

In addition, the maximum speed attained at the approach run ($Vapp_{MAX}$) and the distance of its occurrence from the take-off board (S_{Vmax}) were evaluated using a Stalker ATS 5.02 radar (Applied Concepts Inc., Richardson, TX, USA; sampling rate: 46.9 Hz). The speed radar was fixed at a height of 1 m on a tripod located parallel to the middle axis of the runway 10 m from the far end of the sand pit. The radar was adjusted to be pointed directly at the middle of the lower torso of the jumpers.

2.3. Data Analysis

The $Vapp_{MAX}$ and the S_{Vmax} from the take-off board were calculated after the application of a zero lag, 4th-order Butterworth filter on the acquired data from the speed radar. The cutoff frequency was set at 8 Hz [50].

From all recorded attempts, the attempt with the largest official jump distance was selected for further analysis. From those recordings, the fields containing the midstance of each support phase and the instant of take-off from the board were analyzed using the APAS/WIZARD v. 1.2.59 software (Ariel Dynamics Inc., San Diego, CA, USA). The toe–board distance (TBD) was extracted as the horizontal distance from the take-off line to the athlete's toe of the support foot or the tip of the prosthesis. The TBD was calculated using the contact point and its surrounding four reference markers following the five-point model presented in detail elsewhere (Figure 1) [6]. Each SL was calculated from two consecutive TBDs. The SL adjustments during the preparation for the take-off, namely the larger penultimate ($SL2_{\%ADJ}$) and the shorter last step ($SL1_{\%ADJ}$), were calculated as the percentage difference between the penultimate step to the 3rd-to-last step and the last step to the 2nd-to-last-step, respectively.

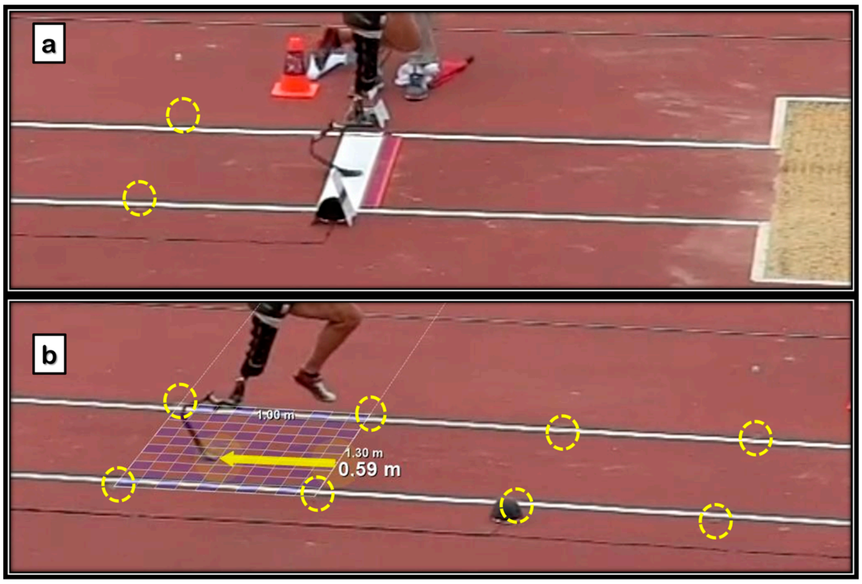

Figure 1. Depiction of the data analysis, with the reference markers indicated in the yellow dashed circles. (**a**) the initiation of the toe–board distance (TBD) measure; (**b**) the TBD measurement at the 3 m marker. In this case, the take-off point of the penultimate step is at a distance of 3.59 m from the take-off line.

Temporal parameters were extracted using the Trimmer module of the APAS 14.1.0.5 software (Ariel Dynamics Inc., USA). The duration of the flight (t_{FL}) and contact (t_C) phase was measured for each step using the time-instants of touch-down (first field depicting ground contact) and take-off (first field presenting the break of the ground contact). In addition, step frequency (SF) and average approach step velocity (SV) were estimated as follows (Equations (1) and (2)):

$$SF = \frac{1}{(t_C + t_{FL})} \quad (1)$$

$$SV = \frac{SL}{(t_C + t_{FL})} \quad (2)$$

The traditional long jump technique involves a larger penultimate and shorter last step [5]; therefore, the steps from the 12th-to-last to the 3rd-to-last were analyzed for asymmetry (5 steps for the take-off side and 5 steps for the non-take-off leg). The inter-limb asymmetry of SL, SF, and SV was quantified between the mean values for the steps conducted with the leg wearing the prosthesis (PWL) and the intact leg (INT) for each participant using the symmetry angle (θ_{SYM}) method [21]. The θ_{SYM} was calculated as presented in Equation (3):

$$\vartheta_{SYM} = \frac{\left(45^o - \arctan\left(\frac{x_{PWL}}{x_{INT}}\right)\right)}{90^o} \times 100\% \quad (3)$$

where θ_{SYM} is the symmetry angle, x_{INT} is the mean value for the INT steps and x_{PWL} is the mean value for the PWL steps. However, if the relationship depicted in Equation (4) occurred

$$\left(45^o - \arctan\left(\frac{x_{PWL}}{x_{INT}}\right)\right) > 90^o \quad (4)$$

then Equation (3) was changed to (Equation (5)):

$$\vartheta_{SYM} = \frac{\left(45^o - \arctan\left(\frac{x_{PWL}}{x_{INT}}\right) - 180^o\right)}{90^o} \times 100\% \quad (5)$$

In the case of positive θ_{SYM} values, the direction of asymmetry indicated a larger INT value, whereas a negative θ_{SYM} indicated a larger PWL value. For the convenience of the comparison of the magnitude of the θ_{SYM} values among the examined step parameters, the absolute θ_{SYM} values were included in the statistical analyses [51].

2.4. Statistical Analysis

Parametrical statistical analyses were run following the results of the Shapiro–Wilk test ($p > 0.05$) for the normality of distribution and Levene's test ($p > 0.05$) for the equality of variance. Paired samples *t*-tests were performed between the x_{PWL} and x_{INT} values. Cohen's *d* was used to estimate the effect size (<0.2: trivial, <0.5: small, <0.8: moderate, and ≥0.8: large) [52] To determine asymmetry, the procedure presented by Exell et al. [51] and Theodorou et al. [6] was conducted.

The relationship of the official distance of the long jump with the examined parameters was investigated with Pearson's correlations. Correlation coefficients (*r*) with absolute values of 0.00–0.10, 0.10–0.39, 0.40–0.69, 0.70–0.89, and 0.90–1.00 were interpreted as negligible, weak, moderate, strong, and very strong correlation, respectively [53].

The IBM SPSS Statistics v.27.0.1.0 software (International Business Machines Corp., Armonk, NY, USA) was used for the statistical analyses. The level of significance was set at $a = 0.05$.

3. Results

The official competition results were 4.49 ± 0.62 m. Figure 2 shows the results for the step temporal and kinematic parameters. A fluctuation between the PWL and INT steps was observed for the examined parameters throughout the approach run. There was a consistent trend for steps from the PWL to have larger SL, t_{FL}, and t_C values than the respective INT steps. Conversely, PWL steps had lower SF compared to the steps commenced from the INT. These observations were not evident for SV.

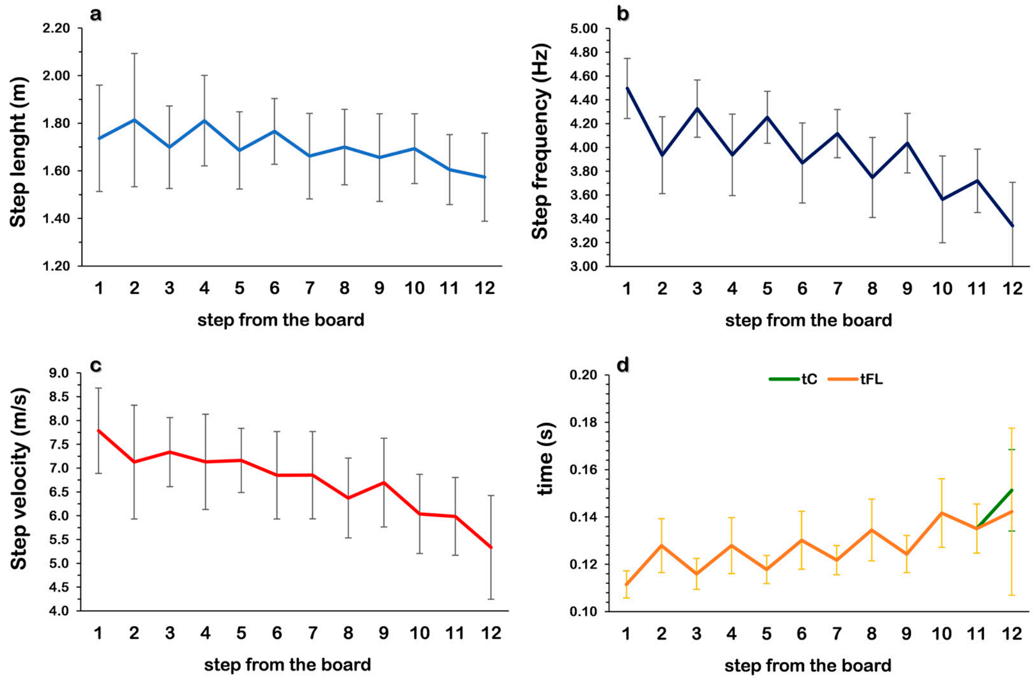

Figure 2. Results for the examined temporal and kinematic parameters. (**a**) step length; (**b**) step frequency; (**c**) average step velocity; (**d**) contact (t_C) and flight (t_{FL}) time.

The results of the examined parameters are presented in Table 1. Half of the examined jumpers (6/12) did not utilize the common technique with a larger penultimate and shorter last step.

Table 1. Descriptive statistics of the examined parameters (n = 13).

Parameter	Minimum	Maximum	Mean	SD	Skewness	Kurtosis
TBD at take-off (m)	0.05	0.16	0.09	0.03	0.96	0.74
$Vapp_{MAX}$ (m/s)	6.14	7.96	7.12	0.59	−0.36	−0.75
S_{Vmax} (m)	1.75	8.54	5.49	2.13	−0.47	−0.33
$SL2_{\%ADJ}$ (%)	−6.40	17.71	4.48	9.26	−0.05	−1.57
$SL1_{\%ADJ}$ (%)	−29.61	14.72	−2.74	15.58	−0.51	−1.26

Note: TBD: toe-to-board distance; $Vapp_{MAX}$: maximum speed attained at the approach; S_{Vmax}: distance from the board where $Vapp_{MAX}$ was achieved; $SL2_{\%ADJ}$: the percentage difference between the length of the 2nd-to-last compared to the 3rd-to-last step of the approach; $SL1_{\%ADJ}$: the percentage difference between the length of the last compared to the 2nd-to-last step of the approach.

Significant ($p < 0.05$) x_{PWL} to x_{INT} difference was observed for SF (Table 2), with the comparison for SV just missing statistical significance ($p = 0.05$). The θ_{SYM} magnitude was 1.79 ± 1.28%, 3.28 ± 2.24%, and 3.19 ± 2.46%, for SL, SF, and SV, respectively. Significant ($p < 0.05$) asymmetry was revealed for SL in 2/12 jumpers, SF in 3/12 jumpers, and SV in 1/12 jumpers. In the case of SV, significant asymmetry occurred in concordance with SF asymmetry.

Table 2. Results (mean ± SD) of the inter-limb comparisons for the step parameters (n = 12).

Parameter	x_{PWL}	x_{INT}	t	p	d
SL (m)	1.71 ± 0.13	1.66 ± 0.15	1.512	0.159	0.38
SF (Hz)	3.69 ± 0.32 *	4.09 ± 0.19	5.331	<0.001	1.52
SV (m/s)	6.37 ± 0.82	6.81 ± 0.72	2.198	0.050	0.57

Note: x_{PWL}: average value for the leg wearing the prosthesis; x_{INT}: average value for the intact leg; SL: step length; SF: step frequency; SV: average step velocity; *: $p < 0.05$ compared to x_{INT}.

Figure 3 depicts the direction of asymmetry. The direction of asymmetry was, for all examined jumpers, towards the INT in SL. As for SL, the direction of asymmetry was towards the PWL for 9/12 jumpers. With regard to SV, the direction of asymmetry was towards the PWL for only 3/12 jumpers, all competing as Class T64.

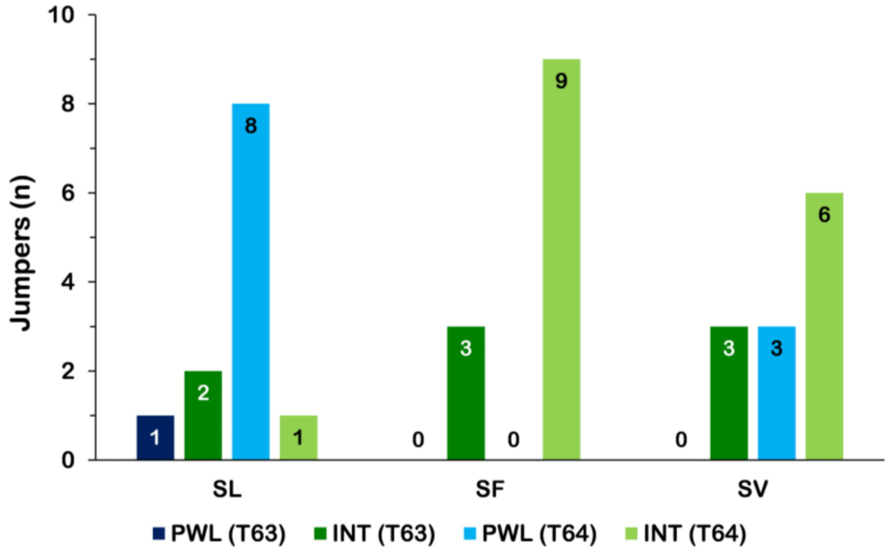

Figure 3. The results for the direction of asymmetry for the T63 and T64 Class female long jumpers (PWL: leg wearing the prosthesis; INT: the intact limb; SL: step length; SF: step frequency; SV: average step velocity).

Finally, the official long jump performance was strongly positively significantly ($p < 0.05$) correlated with $Vapp_{MAX}$ ($r = 0.861$, $p < 0.001$) and moderately negatively correlated to the magnitude of θ_{SYM} for SF ($r = -0.661$, $p = 0.019$).

4. Discussion

This study aimed to evaluate the inter-limb asymmetry of the long jump approach step parameters in Paralympic female Class T63/T64 athletes during competition and to test its relationship with performance. The hypotheses of the study were partially confirmed since significant asymmetries were observed only in a limited number of the examined jumpers. Furthermore, asymmetry in SF only demonstrated a significant correlation with performance.

In the present study, all jumpers executed the take-off using the PWL limb, which is in keeping with previous findings in male jumpers of the same Classes [43]. However, this preference for the take-off leg is not always found, with other previous research reporting an even number of competitors in the Paralympic finals using the PWL and the INT leg as the take-off leg [42]. The use of the PWL as the take-off leg is likely due to the evolution in sports prosthesis technology allowing the transfer of energy generated by the ground reaction forces with decreased energy loss [54]. It was previously reported that jumpers using the PWL for the take-off jumped further through the regulation of their knee stiffness, the utilization of the mechanical properties of their prosthetic limb, and a more effective mechanism of the leg function by reducing the mobility of its proximal joint [28,42].

Unlike previous observations [44], the progression of the step parameters showed a fluctuation between legs. Higher SL and lower SF were observed for the PWL compared to the INT leg. However, this fact did not affect the evolution of the SV, as was observed in able-bodied long jumpers [6]. Previous findings suggest that there is a regulation of the reliance between SL and SF that is more balanced than in sprint running [6]. This regulation is due to the requirement to perform the approach with increased speed but with the spatial constraints of the take-off board and trying to avoid executing a foul jump [4].

No differences were observed for SL between PWL and INT. A previous study in unilateral amputee sprinting showed that inter-limb differences occur in the braking and propulsive impulses [32]. These differences may be the underlying mechanism for the direction of asymmetry in SL being towards the PWL in Class T64 long jumpers. It is also worth noting that a significant number of the examined jumpers (6/12) failed to perform the final steps of the approach using the common "larger penultimate—shorter last step" technique. This technique is essential for the acquisition of optimal biomechanical factors at the initiation of take-off [5,11]. It has been found that there is considerable fluctuation of the vertical body center of mass height during the final steps in amputee long jumpers [41,42] instead of the desired lowering of the body during the penultimate step as a preparation for the take-off [5,7,8]. However, despite this documented mechanical disadvantage [40], elite Paralympic long jumpers were shown to perform an effective take-off by exploiting the properties of their below-the-knee prostheses [45].

The steps performed with the PWL had lower SF than the INT. In addition, the direction of asymmetry was towards the INT for all athletes. When elite Paralympic sprinters were tested [47], results indicated that the prosthesis leg functioned in favor of propulsion, while the intact limb favored braking actions. This difference between the limbs could be the reason for the significant asymmetry revealed in 3/12 jumpers in SF. Past research suggests that the velocity at the late approach should be increased relying on the increment of SF [5] and that female jumpers favor this mechanism more than male jumpers [9]. In general, SF seems to demonstrate a greater prevalence of asymmetry in female long jumpers than in male jumpers [55]. Thus, in the case of the examined T63/64 female long jumpers, the asymmetry in SF imposed by the difference in the mechanical properties between the lower limbs could have led to increases in SL to maintain SV, which resulted in the absence of significant differences and asymmetry in SL and SV.

As mentioned above, asymmetries in SF at the long jump approach run are commonly compensated with alterations in SL that consequently result in no asymmetry in SV [6]. Given the fact that the sprint mechanics of below-the-knee amputees were not considerably different than those of able-bodied jumpers [45], this finding is promising, as emphasis on the execution of the approach run might cause favorable initial conditions for the take-off.

As generally acknowledged, $Vapp_{MAX}$ was significantly positively correlated with the official long jump result. The correlation coefficient found in the present study was similar for below- and above-knee amputees [39], even larger than those reported in the past for elite female amputee athletes [40], and comparable to able-bodied female jumpers [55]. This finding suggests that the athletes in this study were able to take advantage of the speed attained during the approach [40], which is a determining factor for long jump performance [5]. In general, the closing of the performance gap in the long jump between the Olympic and unilateral lower-limb amputee Paralympic jumpers [56] reveals that Paralympic athletes perform the long jump technique effectively using prostheses.

It is important to note the limitations of this study. One limitation is the small sample size of each subgroup (Classes T63 and T64), which is often the case when analyzing elite cohorts. In sprinting, there are no alterations in the inter-limb differences in propulsive and braking forces due to the level of amputation [32]. Nevertheless, as biomechanical differences between below- and above-knee amputees exist in the long jump technique [39–41], it would be beneficial to examine possible differences in the asymmetry of the step parameters between these classes. This comparison could not be conducted in the current study due to the size of the population. In addition, the analysis of only the best attempt restricted the possibility of analyzing step regulation patterns that could add context to the analysis as carried out in the past [44]. Future research in these classes of Paralympic long jumpers could examine both factors to provide further insight into the structure of long jump performance in unilateral amputee jumpers.

5. Conclusions

The examined athletes performed the long jump approach with considerable similarity compared to able-bodied female jumpers, where inter-limb asymmetry in SF is characteristic. Nevertheless, it was found that some athletes did not optimally regulate the last steps to execute a more effective take-off. Coaches and practitioners are encouraged to monitor inter-limb asymmetry of the step kinematics under the perspective of the constrain of the prosthesis, the neuromuscular adaptations for the given task and the effective regulation of step length.

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Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki, and approved by the Institutional Ethics Committee of Universitat de Barcelona (protocol code: IRB00003099/16 November 2011).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

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