Between-Limb Asymmetry in Kinetic and Temporal Characteristics during Bilateral Plyometric Drop Jumps from Different Heights

Running Title: Kinetic and Temporal Asymmetry in Drop Jumps

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Conflict of Interest

Dr Thorsten Sterzing was an employee at Xtep (China) Co Ltd at the time of the study. There is no conflict of interest for all other authors.

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Between-Limb Asymmetry in Kinetic and Temporal Characteristics during Bilateral Plyometric Drop Jumps from Different Heights

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Abstract

This study investigated the between-limb asymmetry in kinetic and temporal characteristics during bilateral plyometric drop jumps from different heights. Seventeen male basketball players performed drop jumps from 3 heights on two platforms in randomized orders. Vertical ground reaction force data were analyzed with respect to the lead limb (i.e. the limb stepping off the raised platform first) and trail limb. Peak forces and loading rates of each limb were calculated. The absolute time differential between the two limbs at initial ground contact and takeoff were determined. The frequency of symmetrical landing and taking off with 'both limbs together' were counted using 3 time windows. Results showed that the lead limb displayed higher peak forces and loading rates than the trail limb across all heights ($p < .05$). As drop height increased, the absolute time differentials decreased at initial ground contact ($p < .001$) but increased at takeoff ($p = .035$). The greater the preset time window, the more landings and takeoffs were classified as bilaterally symmetrical. In conclusion, higher drop heights allowed subjects to become more bilaterally symmetrical in the timing of landing but this reduction in temporal asymmetry did not accompany with any reduction in kinetic asymmetry.

Key Words: *peak force, loading rate, initial contact, takeoff, ground reaction force, time differential*

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INTRODUCTION

Bilateral drop jump is a popular plyometric exercise in strength and conditioning programs, enabling athletes to develop explosive power (14,20) and to improve jump ability (6). Asymmetry in kinetic variables such as ground reaction forces (GRF) and joint kinetics between the left and right limbs have been observed when performing drop jumps from various heights (2,3,17). Between-limb asymmetry can also lead to increased ground contact time (the transition between landing and takeoff) and asymmetrical force production (3), compromising jump height performance (11). Ball and Scurr (2) stressed the importance of simultaneous foot placement in vigorous tasks such as drop jumps to ensure that both limbs receive equal stimulus. To reduce the risk of developing biomechanical imbalances and anterior cruciate ligament injuries, previous work has advocated the correction of between-limb asymmetry by achieving similar kinetic parameters in both limbs (16).

Kinetic parameters during drop jumps from elevated platforms are typically assessed using force platforms. For a fair assessment, it is important to control the centre of mass position prior to leaving the elevated platform. In order to maintain the height of the centre of mass prior to dropping, athletes or research subjects are generally required to step off the elevated platform with one limb, land with both limbs simultaneously, and then perform a maximal vertical jump immediately after landing (3,5,12,20). When using this step-off technique, the limb that leaves the platform first is referred as the lead limb whereas the other limb is referred as the trail limb (3). At low drop heights, there may be insufficient time for the trail limb to catch up with the lead limb before contacting the ground and this may cause between-limb asymmetry during the drop jump. Ball et al. (3) found that the absolute time differential between limbs for initial ground contact was significantly greater at the drop height of 0.2 m (time differential = 0.0067 s) compared with 0.6 m (time differential = 0.00086 s). Using a time differential window of 0.01 s to be considered symmetrical, the authors reported that 37% of subjects exceeded the window when dropping from 0.2 m, compared with only 3.8 % when dropping from 0.6 m.

When comparing single- and double-leg drop jumps, Pain (18) found that elite power athletes had a greater bilateral deficit for jump height and peak power when compared with elite endurance athletes and this is possibly due to power athletes having more fast twitch motor units. Maloney et al (15) investigated unilateral drop jumps from 0.18 m and showed that ankle stiffness asymmetries can explain 79% of the variance of vertical stiffness asymmetries between the two limbs. Peng (20) examined the biomechanical changes during drop jumps of incremental heights from 0.2 to 0.6 m and reported that peak vertical GRF and landing impulse increased with drop height but found no difference in takeoff impulse. This study only presented data pertaining to the dominant limb, determined as the preferred limb to kick a ball, and therefore bilateral comparisons cannot be made. In another study whereby forces of each limb were measured separately using two force platforms, Ball et al. (3) found that bilateral differences in peak vertical GRF were present in drop jumps at low height (0.2 m) but absent at higher heights of 0.4 m and 0.6 m. Their results suggest that temporal and kinetic asymmetry should gradually diminish when there is more time (dropping from higher heights) for the trail limb to catch up with the lead limb. It should be noted, however, that the study by Ball et al. (3) only reported the magnitude but not the direction of the time differential at initial contact. It is therefore unclear whether it was the lead limb or trail limb contacting the ground first. Although it appears reasonable to expect that the between-limb temporal asymmetry is due to the lead limb landing first, empirical evidence from experimental studies is needed to confirm this assumption. In addition, the use of a 0.01-s time window to define symmetry is arbitrary and may be too long since peak vertical GRF during plyometric drop jumping occurred shortly upon landing at approximately 0.10 s (3). Given that the size of the time window can play a critical role in defining symmetry, it is necessary to systematically examine the effect of the time window on the classification of symmetrical drop jumps.

One study showed that although landing impulse of drop jumps increased with drop heights, the takeoff impulse remained unchanged (20). Another study showed that drop jump at 0.4 m resulted in no bilateral difference in peak GRF (2). The authors suggested that despite the asymmetrical starting posture and muscle preparation strategies, the disparity between the two limbs should be re-addressed during the loading and propulsive phase of the drop jump. Based on this speculation, both limbs should leave the ground simultaneously at the takeoff of a drop jump regardless of the drop height or between-limb asymmetry at initial contact. Previous studies on drop jump asymmetry emphasized the initial contact phase and did not report the time differential at the takeoff (2,3). Thus, it is useful to investigate time differential at takeoff alongside with that at initial contact when studying bilateral drop jumps.

The purpose of this study was to investigate the between-limb asymmetric in kinetic and temporal characteristics of plyometric drop jumps from different heights. Time differential between the two limbs at both initial ground contact and takeoff would be considered, alongside with different sizes of time windows to define temporal symmetry. It was hypothesized that 1) kinetic asymmetry and temporal asymmetry at initial ground contact between the lead limb and trail limb would decrease as drop height increased, 2) there would be no temporal asymmetry at takeoff regardless of the drop height, and 3) the length of the time window would affect the classification of symmetrical landing and takeoff.

METHODS

Study Design

A repeated measures design was used to examine the differences in vertical GRF and time differential variables among 3 different drop heights (0.31 m, 0.46 m, and 0.61 m). Each subject performed drop jumps from all heights in randomized orders. Kinetic asymmetry was examined via GRF variables including peak force (F) and loading rate (LR) associated with forefoot and rearfoot landings (17). To provide the information on temporal asymmetry, the magnitude and direction of the time differential between the two limbs at initial ground contact and takeoffs were reported.

Subjects

This study was approved by xx *(blinded for review)* University Institutional Review Board (IRB Number *xxx*). Subjects signed a written informed consent form before participating in any of the testing procedures. Seventeen male university students (body mass: 72.2 ± 11.6 kg, stature: 1.76 ± 0.06 m, age: 25.6 ± 3.8 years) participated in this study. The inclusion criteria were 1) male, 2) aged of 18 to 35 years old, 3) shoe size EUR 41 to 43, 4) at least 5 years of basketball playing experience, 5) had competed at school or hall level, and 6) currently playing basketball for at least once a month over the past 6 months. Subjects will be excluded if they 1) had any injury in the 6 months prior to testing, or 2) experienced pain during the test.

Procedures

Subjects performed warm-up exercises using their own routines as they were all active basketball players. In a familiarisation protocol, subjects were instructed to perform 5 practice trials of drop jumps from each of the 3 different heights, progressively from the lowest to the highest. The heights were 0.31 m, 0.46 m, and 0.61 m (a linear increase of 0.15 m between platforms), which were similar to those used in previous studies (12,13). To control for potential influence of footwear, all subjects were asked to wear the same pair of standard make and model of basketball shoes (EUR 42), and a new pair of socks. In this study, the right limb was regarded as the lead limb stepping off the raised platform and the left limb was considered as the trail limb (9). Upon landing with both feet onto the ground, subjects jumped vertically upwards as soon as possible with maximal effort while minimizing the contact time upon landing (1,20). During each drop jump, vertical GRF for the lead and trail limb were recorded separately at 1200 Hz using 2 force platforms (OR6-7-2000, Advanced Mechanical Technology Inc., Watertown, MA, USA) embedded in the ground. Synchronized force data were obtained using a motion capture system and the Cortex software (version 2.6.2.1169, Motion Analysis Corp, Santa Rosa, CA, USA).

Data Processing

Data processing was performed using a custom MATLAB code (v2017b, MathWorks, Natick, MA, US). Initial ground contact and takeoff was identified using a threshold of 10 N in raw vertical GRF (4,19). Vertical GRF signals were filtered with a fourth-order low-pass Butterworth filter at a cut-off frequency of 50 Hz (12). Two peaks of the vertical GRF were extracted: the first peak relating to the forefoot (F_F) impact, and the second peak relating to rearfoot (F_R) impact (3). The mean loading rates for forefoot (LR_F) and rearfoot (LR_R) impacts were calculated between 20-80% of the slope before each peak (17). All GRF data were normalized to subjects' body weight (BW). Across the 5 trials per height, intra-class correlation (ICC) analysis showed good inter-trial reliability and therefore the mean of 5 trials was used (ICC across 3 heights, F_F = .894, F_R = .777, LR_F = .794, LR_R = .819).

For time differential variables, the differences at initial ground contact (t_i) and takeoff (t_{off}) were calculated. A positive t_i indicated the lead limb landed first and a negative t_i indicated the trail limb landed first; a positive t_{off} indicated the lead limb took off first and a negative t_{off} indicated the trail limb took off first. To illustrate the magnitude of time differential without the influence of direction, the absolute time differentials of t_i and t_{off} for each trial were also calculated (3). At each drop height, the average absolute value of 5 trials per subject were used for statistical analysis.

Next, the frequency of symmetrical drop jumps was counted from t_i and t_{off} values using different time windows. While theoretically zero time differential would mean that both limbs landed or took off at exactly the same time, the sampling rate of the equipment should be considered when setting a cut-off threshold to define symmetry. In the present study, 3 different time windows were compared: small 0.0008 s, medium 0.004 s, and large 0.008 s. The small window was set based on the sampling frequency of the force platform in the present study (1 s/1200 Hz = 0.0008 s). The medium and large windows were set 5 and 10 times of the small window, respectively. The medium (0.004 s) and large (0.008 s) windows would correspond well with one time frame of high speed videos sampled at 240 Hz (1 s/240 = 0.004 s) and 120 Hz (1 s/120 = 0.008 s). Using these 3 windows, each drop jump (5 jumps × 3 drop heights × 17 subjects = 255 trials) were categorized as 'lead limb first', 'trail limb first', or 'both limbs together' at initial and takeoffs. This method can illustrate the percentage of symmetrical landing and takeoff as each drop height and how the length of the time window can affect the categorization.

Statistical Analyses

To illustrate within-subject variations among the 5 trials, the between-limb differences in each kinetic and temporal variable at each drop height were plotted for visual comparison. Using 3 time windows, the frequency of 'lead limb first', 'trail limb first', and 'both limbs together' at initial ground contact and takeoff at each drop height were graphically compared. To examine the influence of time window (small, medium, large), the number of symmetrical landings and takeoffs were statistically compared using the Pearson's chi-square test.

Inferential statistics were performed on kinetic and temporal variables using SPSS (version 25.0, SPSS, Inc, Armonk, NY, USA). Normality was checked using the Shapiro-Wilk test. For kinetic variables, a two-factor (3 drop heights × 2 limbs) repeated-measures analysis of variance (ANOVA) was used to determine the statistical significance ($\alpha = 0.05$) For absolute time differentials, a one-way repeated measures ANOVA was used. To correct for any violation of sphericity, significance was assessed from the Greenhouse-Geisser correction. Effect size of ANOVA was calculated as partial eta squared (η_p^2). *Post-hoc* tests with Bonferroni corrections were applied where appropriate. To indicate the magnitude of the between-limb differences, a symmetry index (SI) for each kinetic variable was also calculated as:

$$SI = \frac{|x_{Lead} - x_{Trail}|}{0.5\ (x_{Lead} + x_{Trail})} \times 100\%$$

where x_{Lead} refers to the variable of the lead limb, and x_{Trail} refers to the variable of the trial limb.

RESULTS

Kinetic Variables

Peak vertical GRFs and loading rates at forefoot and rearfoot were significantly higher as height increased (Table 1). There were significant between-limb differences in all kinetic variables, with the lead limb experiencing higher peak forces and loading rates compared with the trail limb across all drop heights. No height × limb interaction was observed. The symmetry index ranged from 9.8% to 27.9% across all 3 heights. There were some variations among the 5 trials per participant and also inter-individual differences among the 17 participants in peak forces (Figure 1) and loading rates (Figure 2).

*****Table 1 about here****

***** Figure 1 and 2 about here****

Temporal Variables

Visual plots of time differentials at initial ground contact and takeoff showed that there were within-subject variations in the landing and takeoff patterns among the 5 trials at each drop height (Figure 3). Although all subjects stepped off from the elevated platform with the lead limb first, they did not necessarily land with the lead limb first. Subject 9 even consistently landed with the trail limb first at a drop height of 0.46 m. As drop height increased, the absolute time differential decreased at initial ground contact but increased at takeoff (Table 2). This indicates that as the drop height increased, the subjects were more symmetrical at landing but less symmetrical at takeoff in terms of timing.

*****Figure 3 about here****

*****Table 2 about here****

Time Window

The length of the preset time window affected the categorization of symmetrical landing substantially (Figure 4). The larger the time window, the more symmetrical landings with 'both limbs together' at 0.31m ($\chi^2(2) = 24.21$, $p < .001$) ,0.46 m ($\chi^2(2) = 55.37$, $p < .001$), and 0.61 m ($\chi^2(2) = 80.32$, $p < .001$). When the small window (0.0008 s) was used, less than 3% of landing and takeoff was considered symmetrical. Based on the medium (78.6%) and large time windows (67.9%), most landing from 0.31 m were classified at 'lead limb first'. This between-limb asymmetry diminished with higher drop height as reflected by more 'both limbs together' landings at 0.61 m (medium window 39.8%, large window 69.9%).

*****Figure 4 about here****

At takeoff, the percentage of symmetrical takeoffs slightly decreased with higher drop heights (Figure 2). Drop height seems to affect the temporal asymmetry at takeoff to a lesser extent than at initial ground contact. The larger the time window, the more symmetrical takeoffs with 'both limbs together' at 0.31m ($\chi^2(2) = 77.07$, $p < .001$) ,0.46 m ($\chi^2(2) = 70.93$, $p < .001$), and 0.61 m ($\chi^2(2) = 60.91$, $p < .001$). Across all drop heights, about one-third of takeoffs (30.5%

to 42.9%) were considered symmetrical using a medium window. With a large window, more than half of takeoffs were classified as bilateral symmetrical (56.6% to 65.5%).

DISCUSSION

The purpose of this study was to investigate the between-limb asymmetry in kinetic and temporal characteristics of drop jumps from different drop heights, taking into consideration how different time windows could influence the categorization of bilateral symmetrical landings or takeoff. The main findings are: 1) higher peak forces and loading rates were consistently found in the lead limb than the trail limb across all 3 drop heights, while absolute time differential at initial contact decreased with drop height; 2) at the takeoff, subjects were less bilateral symmetrical in the takeoff timing as the drop height increased; and 3) the length of the time window substantially affected the classification of bilateral symmetry, with a larger time window resulting in more symmetrical landings and takeoffs.

Kinetic and Temporal Asymmetry

The first hypothesis of the present study was that kinetic asymmetry and temporal asymmetry at initial ground contact between the lead limb and trail limb would decrease as drop height increased. This hypothesis was partly supported by our findings. For kinetic variables, peak vertical GRFs and loading rates were higher in the lead limb than the trail limb in all 3 drop heights but this bilateral difference did not diminish with higher drop heights (Table 1). The consistent kinetic asymmetry regardless of drop height was in contrast with the study by Ball et al (3) which reported bilateral differences in peak vertical GRF in drop jumps at low height (0.2

m) but not at higher heights (0.4 m and 0.6 m). The lack of differences at higher height in the study of Ball et al (3) may be related to their small sample size of 10 participants and hence lacking statistical power. Taking 3 drop jump trials per height, previous work reported that the reliability of kinetic variables was lower at higher height (0.5 m and 0.6 m) than that of lower heights (0.4 m and below) (20). Compared with Ball et al. (3) who took 3 trials per height, the present study allowed 5 attempts and obtained good ICC even for 0.61 m drop jumps. For temporal variables, the absolute time differential between the two limbs at initial ground contact decreased as drop height increased (Table 2). This reduction in the magnitude of temporal asymmetry at initial contact with increasing drop height supports our first hypothesis and is also consistent with Ball et al. (3) which found a negative relationship between drop height and absolute time differentials at initial contact. Thus, our study supported that as the subjects had more time in the air for the trail limb to catch up with the lead limb, they became more bilaterally symmetrical in the timing of landing.

Previous studies suggested that the between-limb kinetic asymmetry in drop landing or drop jumping was caused by the step-off technique and/or temporal asymmetry due to the trail limb not having sufficient time to catch up with the lead limb (3,9). Our results showed that with higher drop heights and hence more time in the air, subjects did become more bilaterally symmetrical at the time of initial ground contact. This reduction in temporal asymmetry, however, did not accompany with a reduction in kinetic asymmetry as GRF and loading rate variables were consistently higher in the lead limb than the trail limb across all drop heights. Furthermore, despite all subjects initiated the drop jump with the lead limb leaving the raised platform first, the bilateral asymmetry at initial contact were not all due to the lead limb landed first (Table 3). Out of the 255 drop jumps, 54 trials were landed with the trail limb first across all drop heights (0.31 m: 10 trials, 0.46 m: 17 trials, 0.61 m: 27 trials). Collectively, results from the present study clarified that temporal asymmetry at initial contact could not fully explain the between-limb kinetic asymmetry observed in jump drops. Factors such as limb preference (7) and training background (22) may have played a role in causing some between-limb kinetic differences in drop jumps. As higher GRFs and loading rates on one limb seemingly indicate that the subject has placed greater weight on that limb, this would suggest that the limb had taken a functional lead compared to the other. Athletes routinely performing drop jumps in their training may gradually overload the limb that takes the functional lead, and this may have implications on chronic injuries. Since kinetic asymmetry persists regardless of drop height and cannot be visually observed based on the timing of landing, bio-feedback systems monitoring landing forces are recommended in correcting uneven loading between the two limbs.

The second hypothesis of this study was that there would be no temporal asymmetry at takeoff regardless of the drop height. This hypothesis was rejected since we found a significant decrease in the absolute time differential at the takeoff when drop height increased (Table 2). It is worth noting that drop height affected the temporal asymmetry at takeoff to a lesser extent than at landing (Figure 2, Table 3). One previous study reported no bilateral difference in peak vertical GRF in drop jump from 0.4 m (2), suggesting that the between-limb disparity at the beginning of a drop jump should be re-addressed during the loading and propulsive phase the jump. In this earlier study, however, no information on time differential at takeoff was presented to show that subjects had indeed became bilaterally symmetrical at the time of takeoff. Results from the present study demonstrated that between-limb temporal asymmetry at the takeoff of drop jumps exist and the magnitude of asymmetry increased with drop heights. Unlike the temporal asymmetry at initial contact which was predominantly due to the right limb (lead limb) landing first, there were considerable jump trials that were taken off with the left limb (trail limb) first especially at higher drop heights (Figure 1). The takeoff asymmetry could be due to limb preference when initiating a maximum jump, considering that the basketball players recruited in this study were all right-handed who tended to jump off on their left limb more in order to perform a lay-up to shoot with their right arm.

In the present study, we followed the literature (9) to term the limb leaving the raised platform first as the 'lead limb'. From the results, it is interesting to note that leading by the timing of leaving the raised platform does not always result in contacting the ground first. This observation questions whether 'lead limb' and 'trail limb', defined by the timing of leaving the raised platform, are good terminologies that can be generally applied to athletes with varied limb preference. There can also be implications to practitioners who aim to increase the stimulus of a particular limb with the assumption that the 'lead limb' would hit the ground first. In reality, the target stimulus may not be reached because the 'lead limb' does not always contact the ground first and it is not always associated with higher loading.

Time Window of Defining Bilateral Asymmetry

The third hypothesis of the present study was that the length of the time window would affect the classification of symmetrical landing and takeoff. This hypothesis was supported by our results. Using 3 different time windows to classify bilateral symmetrical landing and takeoff showed clearly that the larger the size of the time window, the more symmetrical takeoffs and landings were counted (Figure 4). Currently, there is no standard or commonly accepted value for setting the time window that defines temporal symmetry. Ball et al. (3) employed an arbitrary window of 0.01 s as time threshold to classify whether subjects performed temporally symmetrical drop jumps at initial contact. It was found that 37% of subjects exceeded the window (i.e. *not symmetrical*) when dropping from the lowest drop height (0.2 m), compared with only 3.8 % at when dropping from the highest drop height (0.6 m). Alternatively, it would mean 63.0% and 96.2% of subjects were considered symmetrical at the lowest and the highest drop heights, respectively. Based on our large window of 0.008 s which was similar to the 0.01 s window by Ball et al. (3), we found less number of symmetrical landing at initial ground contact that were classified as 'both limbs together' at the lowest (0.31 m: 28.6%) and highest (69.9%) drop heights. The pattern that more symmetrical landings with higher drop heights were consistent between our study and that by Ball et al (3).

When classifying bilateral symmetry using the small window (0.0008 s), the interpretation of bilateral coordination for simultaneous drop jumps can be completely different from that using the large window. Considering that less than 3% of landings and takeoffs were done with both limbs together (Figure 4), it may be concluded that between-limb temporal asymmetry exists almost in all jumps (> 97%) and is not influenced by drop heights. The drastic difference in result interpretations highlights that what constitutes as temporal symmetry between the two limbs at landing and takeoff is severely dependent on the preset time window. In the present study, the rationale of investigating the implications of 3 different time windows was based on the temporal characteristics and sampling frequency of various equipment that are commonly used to evaluate drop jumps. For example, force platforms are typically operated at 1000 Hz to 1200 Hz (small window) (2,3). High speed video cameras or optical motion capture systems often sample at a frequency of 240 Hz (medium window) (19,23) or 120 Hz (large window) (10,24). In-shoe plantar pressure measurements during jumping and landing tasks can also be sampled at 100 Hz. (8,21). One may argue that it is unrealistic to expect human subjects to coordinate within a very small time threshold of 0.0008 s based on the temporal characteristics of highly precise equipment. The time window, however, cannot be too large as the ground contact phase of jumping tasks is very short and that peak vertical GRF can occur shortly upon landing at approximately 0.10 s (3). While it is premature to recommend a fixed time window to define bilateral symmetry, results from the present study clearly illustrated that the size of the time windows employed would lead to varied interpretations of the same dataset. Hence, caution should be taken when comparing results from studies using different methods of examining bilateral asymmetry. Future efforts in seeking an appropriate time window of defining between-limb temporal asymmetry are warranted.

Limitations

One limitation of the present study was that only the right limb was used as the lead limb in the drop jumps. Incidentally, all participants also reported that their dominant limb was the right limb. Future studies can conduct experiments with subjects stepping off the elevated platforms with both left limb first and right limb first conditions. Such study design can confirm if peak forces and loading rates are consistently higher in the one limb, regardless of whether that limb was the lead or the trail limb when stepping off. It would be of interest to also allow subjects to self-select their preferred lead limb to step off the platform. Another limitation was that the subjects were homogenous as male, recreational basketball players and hence the results may not be applicable to females or athletes engaged in other sports. Since plyometric drop jumps are performed as strength and conditioning exercises across athletes in many different sports, it will be useful to confirm the present findings in other athletic populations. Lastly, the present study focused only on peak forces and loading rates during the landing phase of drop jumps and did not consider the propulsive phase. Future studies can examine the kinetic (e.g. impulse) and kinematic (e.g. joint angles) profiles of different phases of the drop jumps to enhance the understanding of how temporal asymmetry is related to kinetic asymmetry.

Conclusion

Kinetic and temporal asymmetry in drop jumps existed between the left and right limbs across different drop heights. As drop height increased, subjects become more bilateral symmetrical at the time of landing but less symmetrical at takeoff. The reduction in temporal asymmetry at landing, however, did not accompany with any reduction in kinetic asymmetry as peak forces and loading rate variables were consistently higher in the lead limb than the trail limb across all drop heights. Thus, temporal asymmetry at initial contact could not fully explain the between-limb kinetic asymmetry observed in jump drops. Factors such as limb preference and training background should also be considered. When examining temporal characteristics, the length of the time window used to define bilateral symmetrical plays a crucial role and would lead to varied interpretations of the same dataset. Athletes routinely performing drop jumps in their training may overload the limb that takes the functional lead, and this may have implications on chronic injuries. Bio-feedback systems monitoring landing forces may be useful in correcting uneven loading between the two limbs. In terms of methodology, coaches and scientists should be aware that between-limb differences in timing can be affected by the sampling rate of the equipment and the choice of time window set to define temporal symmetry.

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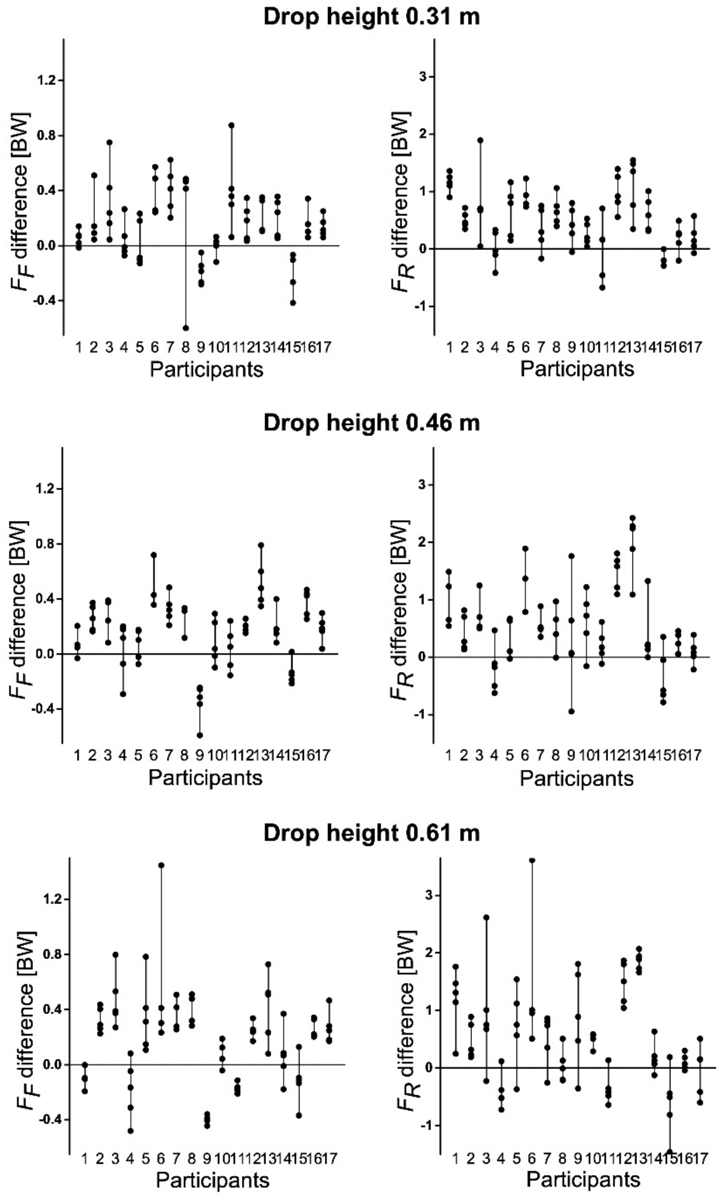
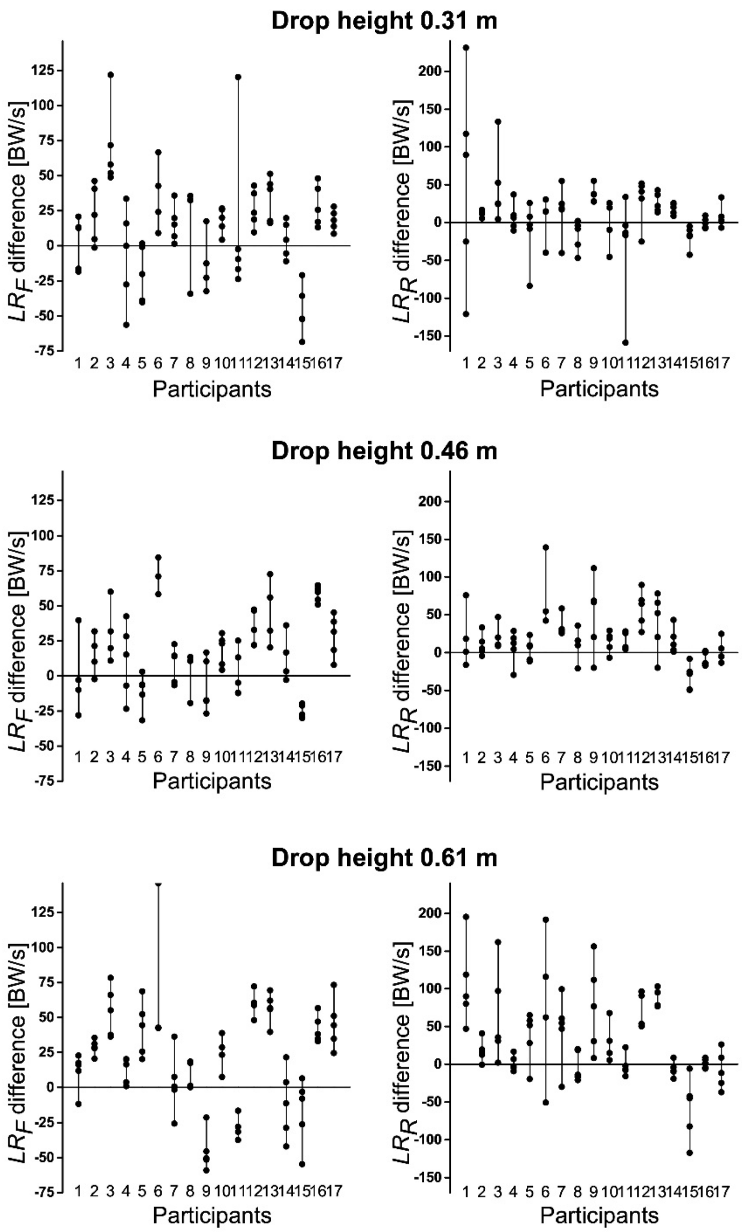
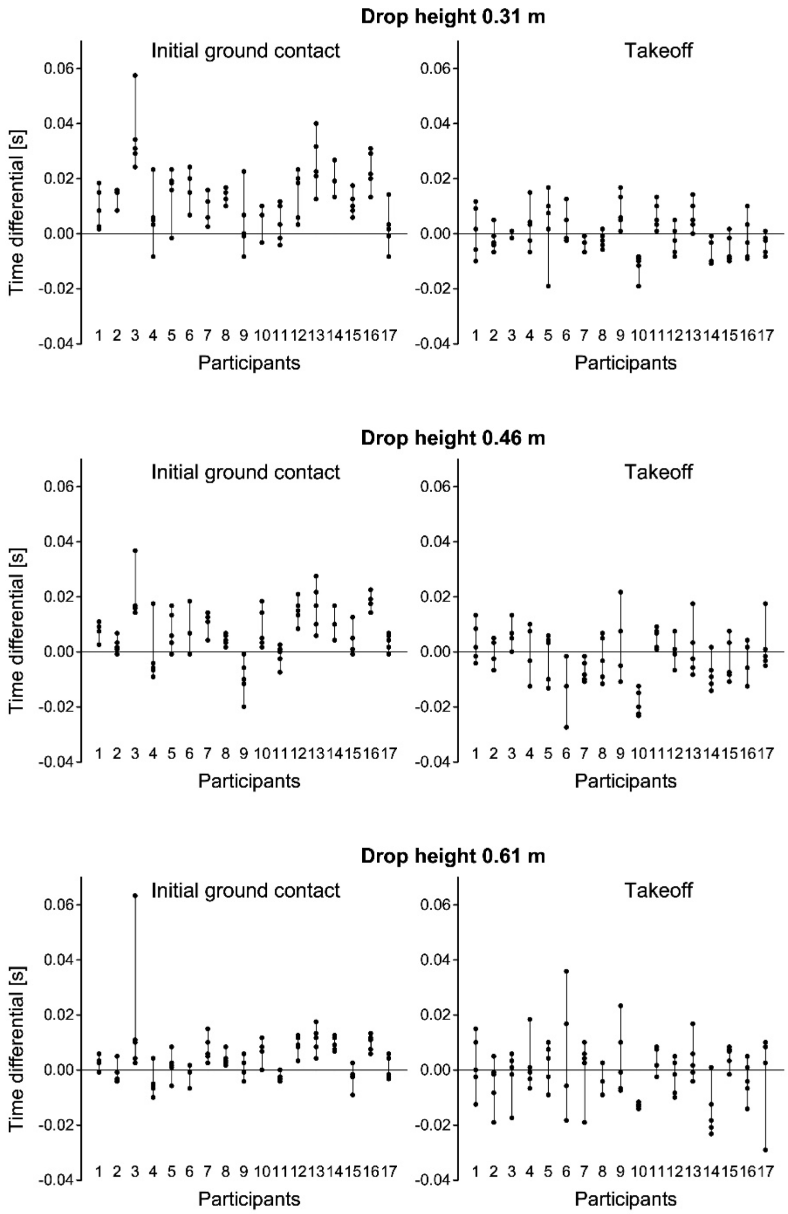

Drop height 0.31 m
Drop height 0.46 m
Drop height 0.61 m
F_F difference [BW]
F_R difference [BW]
Participants

Figure 1



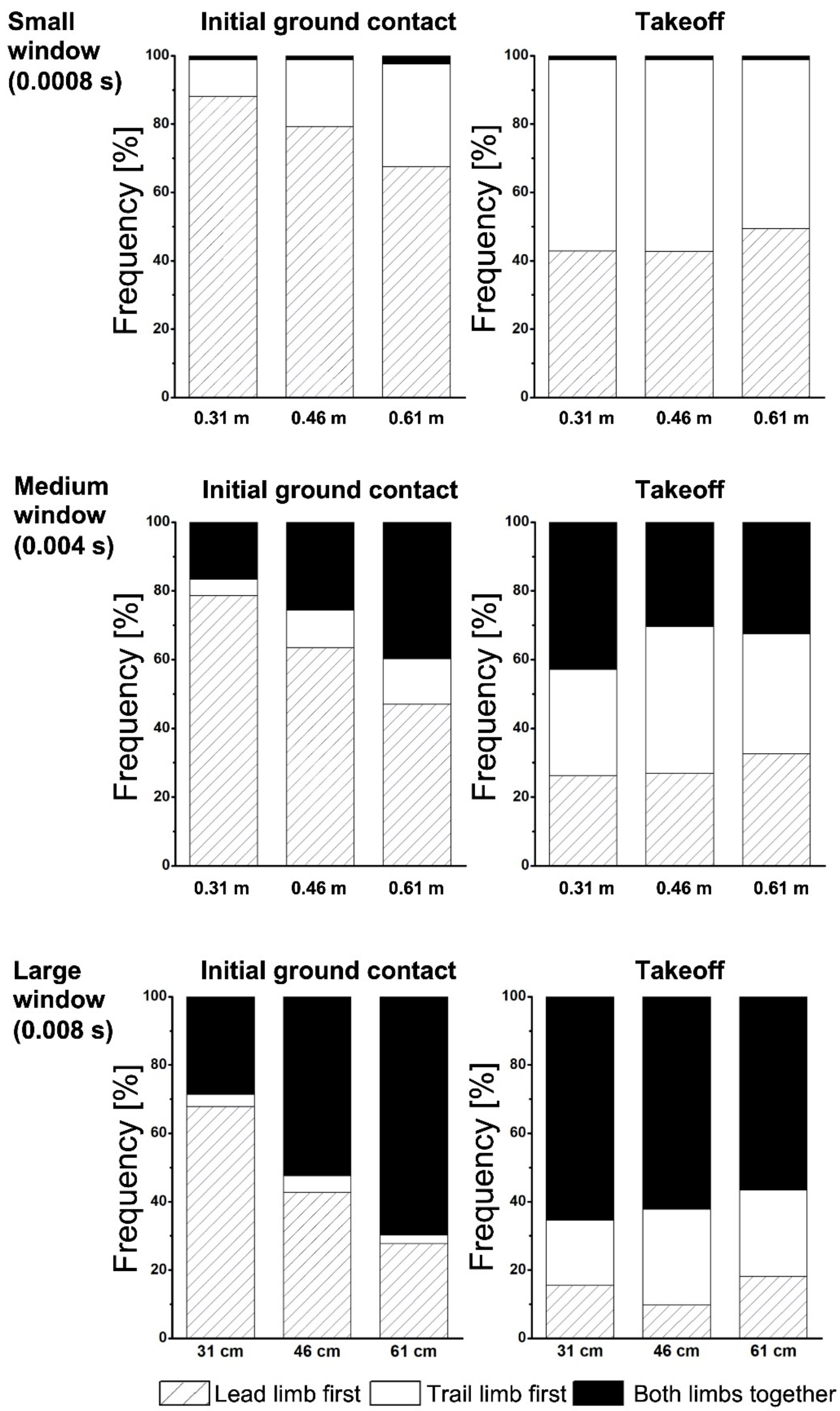
Drop height 0.31 m
LR_F difference [BW/s]
LR_R difference [BW/s]
Participants
Drop height 0.46 m
Drop height 0.61 m

Figure 2



Drop height 0.31 m
Initial ground contact
Takeoff
Time differential [s]
0.06
0.04
0.02
0.00
-0.02
-0.04
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17
Participants
Drop height 0.46 m
Drop height 0.61 m

Figure 3



Small window (0.0008 s)
Initial ground contact
Takeoff
Frequency [%]
0
20
40
60
80
100
0.31 m
0.46 m
0.61 m
Medium window (0.004 s)
Initial ground contact
Takeoff
Large window (0.008 s)
Initial ground contact
Takeoff
31 cm
46 cm
61 cm
Lead limb first
Trail limb first
Both limbs together

Figure 4

Table 1 Ground reaction force variables and symmetry index (SI) in drop jumps from 3 heights (n = 17).

Variables	Leg	0.31 m	0.46 m	0.61 m	Height		Leg		Interaction	
					p	η_p^2	p	η_p^2	p	η_p^2
F_F [BW]	Lead	0.82 (0.24)	1.18 (0.28)	1.61 (0.36)	**<0.001**	0.951	**0.007**	0.377	0.060	0.179
	Trail	0.68 (0.18)	1.01 (0.28)	1.46 (0.31)						
	SI	18.7%	15.5%	9.8%						
LR_F [BW/s]	Lead	88.66 (28.08)	125.67 (30.44)	176.61 (38.28)	**<0.001**	0.912	**0.022**	0.288	0.118	0.125
	Trail	79.40 (34.27)	107.57 (32.61)	157.22 (44.52)						
	SI	11.0%	15.5%	11.6%						
F_R [BW]	Lead	2.27 (0.56)	2.83 (0.67)	3.38 (0.92)	**<0.001**	0.849	**0.001**	0.495	0.521	0.040
	Trail	1.77 (0.39)	2.26 (0.39)	2.90 (0.61)						
	SI	24.8%	22.4%	15.3%						
LR_R [BW/s]	Lead	66.02 (53.65)	82.00 (51.99)	123.22 (78.93)	**<0.001**	0.633	**0.019**	0.300	0.627	0.029
	Trail	55.37 (42.16)	61.96 (39.29)	93.01 (54.26)						
	SI	17.5%	27.8%	27.9%						

Note. F_F = maximum vertical GRF for forefoot, LR_F = loading rates for forefoot, F_R = maximum vertical GRF for rearfoot, LR_R = loading rates for rearfoot. Data are expressed in mean (standard deviation). Significant *p*-values (p <.05) are shown in bold.

Maximal vertical GRF relating to the forefoot (F_F) and rearfoot (F_R) impact peaks were extracted using a custom MATLAB code (v2017b, MathWorks, Natick, MA, US). The mean loading rates for forefoot (LR_F) and rearfoot (LR_R) were calculated between 20-80% of the slope before each peak. Effect size of ANOVA was calculated as partial eta squared (η_p^2).

Table 2 Absolute time differentials between the lead and trail limbs at initial ground contact and takeoff of drop jumps from 3 heights (n = 17).

Absolute time differential	0.31 m	0.46 m	0.61 m	p	η_p^2
Initial ground contact [s]	0.014 (0.019)[bc]	0.009 (0.001)[ac]	0.006 (0.001)[ab]	<0.001	0.627
Takeoff [s]	0.006 (0.0007)[c]	0.007 (0.0008)	0.008 (0.0008)[a]	0.024	0.209

[a]significantly differed from 0.31 m; [b]significantly differed from 0.46 m; [c]significantly differed from 0.61 m; effect size of ANOVA was calculated as partial eta squared (η_p^2).