



## Brief Report

# Do Outcome or Movement Strategy Variables Provide Better Insights into Asymmetries During Multiple-Hops?

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## Abstract

Multiple-hops performed horizontally in series effectively assess return-to-play readiness, as they mimic the propulsive and decelerative demands of sports. Movement strategy variables (kinetic variables) offer more insight into injury recovery than outcome-based measures (kinematic variables) like hop distance alone. This study focused on kinematic and kinetic variables to assess asymmetries during triple-hop (3-Hop) and quintuple-hop (5-Hop) tests with 44 male athletes from university sports clubs and teams. The aim was to determine the magnitude and potential direction of asymmetry and compare the sensitivity of kinematic and kinetic variables. Results showed mean kinematic asymmetries below 7.1% (range: 0.00 to 28.9%), while average kinetic asymmetries were as high as 38.8% (range: 0.0% to 95.4%). These findings suggest that kinetic variables are more sensitive in assessing movement strategy, providing more detailed insight into rehabilitation and return-to-play decisions. The study emphasizes the importance of considering both outcome and movement strategy variables in injury recovery. These results have practical applications for clinicians and coaches supporting those in return-to-play scenarios, as well as those addressing performance deficits, therefore offering valuable information to refine exercise prescriptions and athletic program design.

**Keywords:** braking-demand; asymmetry; return-to-play



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## 1. Introduction

Acyclic and cyclic jumps are commonly used to assess limb asymmetry, serving as key indicators of injury risk in rehabilitation management and return-to-play protocols. These jump assessments, conducted with either vertical or horizontal force orientations, offer insights into an individual's neuromuscular status. When evaluating horizontal asymmetry, the single-leg hop, triple-hop (3-Hop), and crossover-hop are the most commonly used assessments [1–5]. Davey et al. (2021) [1] concluded that the 3-Hop assessments display greater ecological validity for team sport athletes, closely mimicking the propulsive and decelerative force demands associated with short ground contact times (GCT) typically observed in these sports. Despite this suggested validity, the reliability measures reported by researchers [2] and their demonstrated application in rehabilitation settings raise concerns that discrete distance values (outcome variables) alone do not adequately capture

the nuances of movement strategy [4]. Consequently, Kotsifaki et al. (2022) [4] suggested that a more comprehensive understanding of 3-Hop asymmetry could be achieved by integrating outcome variables with those reflecting underlying movement strategies, through kinetic analysis.

Researchers [1,3,6] have investigated the usefulness of 3-Hop flight times or hop distances divided by GCT, also known as horizontal reactive strength indexes ( $RSI_{hor}$ ), in quantifying asymmetry. The main findings from these research groups were: (1) 3-Hop distance alone masked residual deficits in reactive strength performance; thus, more detailed analyses of individual hop performance may be warranted [3]; (2) although only trivial to small differences in mean asymmetry were observed, significant within-group variation was noted, highlighting the importance of also analyzing data individually [1]; (3) the direction of asymmetry can fluctuate between hops and test sessions, underlining the value of also monitoring the direction of the imbalance [1]; (4) vertical and horizontal reactive strength indexes show a poor level of agreement, and when calculating  $RSI_{hor}$ , flight time and hop distance should not be used interchangeably [5]; and (5) Davey et al. (2021) determined 3-Hop  $RSI_{hor}$  both within and between sessions to be highly reliable in a group of adolescent male American football players [1].

It is important to note that research on 3-Hop asymmetry so far has focused on basic kinematic outcome strategy variables, which have been determined reliable using a simple measuring tape or using basic smartphone video capture [7,8]. Performance-based outcome variables, such as hop distance, overlook the movement strategies or kinetic demands that contribute to these results. Key elements of movement strategy involve kinetic aspects, such as vertical and horizontal braking and propulsion forces or impulse, that influence kinematic variables like flight time and ground contact duration for each hop [9]. Kinetic variables, such as vertical and horizontal braking and propulsive impulses and forces determined using force platforms, may therefore provide deeper diagnostic insights into cyclic asymmetry and guide more effective exercise prescriptions. Furthermore, Kotsifaki et al. (2021) [10] reported that athletes post-ACLR (anterior cruciate ligament reconstruction) were nearly symmetrical in terms of hop distance (within 3% difference), yet they still displayed moderate to large differences in knee function during propulsion (69%). This is further supported by evidence showing that athletes have returned to sport after rehabilitation but still exhibit significant functional deficits in limb symmetry [11,12]. Furthermore, the authors of this study have observed that individuals who manage the stretch-load demands of the 3-Hop assessments (approximately 3.3 to 4.3 bodyweights) can struggle with the higher stretch-load demands associated with the later landings of the quintuple-hop (5-Hop) assessments (approximately 3.3 to 5.2 bodyweights) [13]. Given the increased stretch-loading in the 5-Hop, greater levels of asymmetry may be detectable in the latter hops in those unable to attenuate these increased biomechanical demands. With this information, the primary focus of this paper is to understand the utility of 3-Hop and 5-Hop kinematics (outcome variables) and kinetics (movement strategy variables) in describing vertical and horizontal cyclic asymmetries. Specifically, the aims were to: 1) determine the magnitude and direction of asymmetries; 2) assess whether kinematic and/or kinetic variables demonstrate greater asymmetry for the same movement; 3) compare vertical and horizontal asymmetries across hops; and 4) evaluate if the magnitude of asymmetry differs between the 3-Hop and 5-Hop assessments. It was hypothesized that increased asymmetries will be evident in the kinetic measurements of hops that require higher stretch-loads, particularly in the vertical and horizontal braking impulses during hops 3 and 4 of the 5-Hop test.

## 2. Methodology

### 2.1. Participants

Forty-four male university athletes (age:  $20.1 \pm 1.4$  years; body mass:  $71.2 \pm 8.6$  kg; height:  $171.9 \pm 5.1$  cm) from a wide range of sports disciplines and expertise from novice to elite; including kendo, baseball, rowing, athletics, windsurfing, cycling, soccer, and basketball volunteered to participate in this study. All subjects were required to be healthy and free from injury at the time of testing. Those with a history of major musculoskeletal injuries (e.g., ruptures or tears of key tendons or ligaments such as the Achilles tendon or anterior cruciate ligament) were excluded, regardless of rehabilitation status. Ethical approval was obtained from both the Auckland University of Technology Ethics Committee (Reference: 17/133) and the National Institute of Fitness and Sports in Kanoya Ethics Board (Reference: 8-123) and study procedures adhered to the Declaration of Helsinki. All subjects provided written informed consent. Body mass was measured to the nearest 0.1 kg, and height was assessed using standard protocols from the International Society for the Advancement of Kinanthropometry [14], using a digital scale and stadiometer (Tanita DC-217A, Tokyo, Japan).

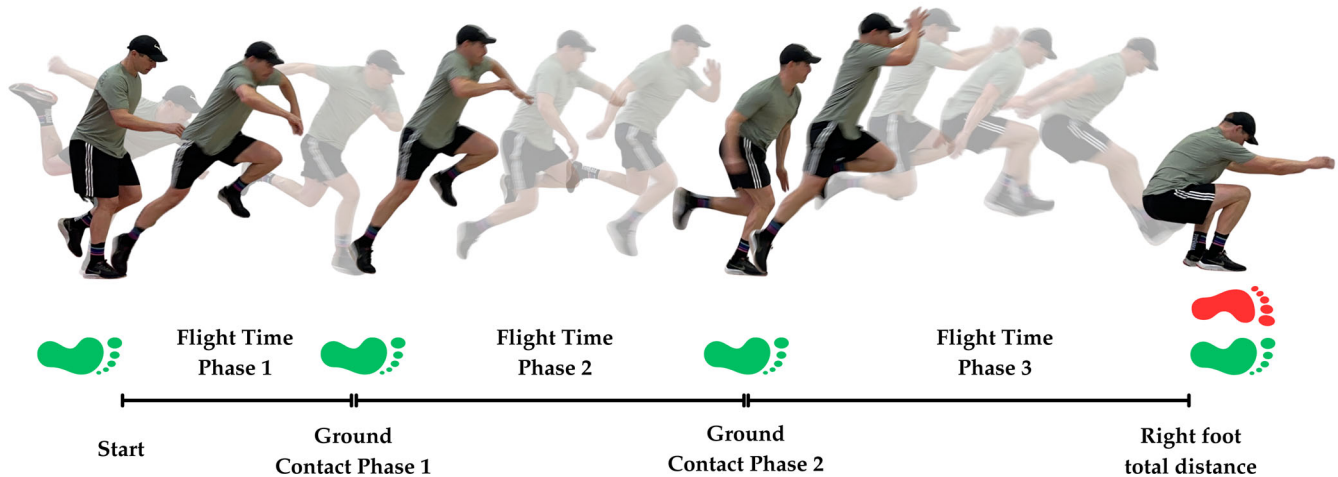
### 2.2. Procedures

Subjects completed a familiarization session at least three days prior to testing. This included a standardized warm-up protocol, approximately 20 min in length, which was repeated on the day of testing. The time of testing varied between a morning or afternoon session; however, ambient temperature was consistent at 10–12 degrees centigrade in an indoor training facility. The warm-up involved dynamic stretching exercises for both upper and lower limbs, general movement to increase body temperature, explosive bounding drills to replicate the demands of the tests, and progressively faster 30 m sprints. Testing began five minutes after the warm-up.

The 3-Hop and 5-Hop tests consisted of three and five consecutive horizontal hops, respectively, performed on the same leg (Figure 1). The reliability of these tests has been determined previously [7,8]. Due to the high physical demands of these tests, subjects completed three trials of the 3-Hop and two trials of the 5-Hop in a randomized order for both dominant and non-dominant legs. In this study, dominance was determined by their 'kicking limb', as has been determined and commonplace in other similar studies [15]. A two-min rest period was provided between trials and before switching legs to reduce fatigue and injury risk. Each trial began with the participant balancing on one leg before initiating the hops. After the final hop, subjects were instructed to land on both feet. Touching the ground with the hands was permitted, provided the hopping foot did not advance after landing. This approach encouraged maximal horizontal distance. Arm movement was allowed to reflect natural athletic coordination. Subjects were instructed to "cover the greatest horizontal distance in the shortest amount of time".

All hop trials were performed on an indoor synthetic track surface (Hasegawa Sports Facilities, Tokyo, Japan), which housed a series of 54 embedded force platforms (TF-90100, TF-3055, TF-32120; Tec Gihan, Kyoto, Japan). These platforms were connected to a single computer system for synchronized data acquisition. Ground reaction forces (GRFs) were recorded at a sampling rate of 1000 Hz for each trial.

The force data were captured, exported, tagged, and stored for subsequent analysis. GRF signals were processed using a fourth-order Butterworth low-pass digital filter with a 50 Hz cutoff frequency to remove any mechanical or electrical 'noise' from the force platform itself. From these filtered data, both horizontal and vertical components of propulsive and braking kinetics were extracted. Impulses were calculated by integrating the GRF signals over the appropriate time intervals.



**Figure 1.** The sequence of a right foot 3-Hop test (green).

Vertical braking impulse was defined as the period from the moment of initial heel strike to the point where the center of pressure (COP) crosses the zero axis at the anterior–posterior transition, assuming that the subject’s center of mass was directly above the foot at this point, as previously described [16,17]. This classification was internally validated with high consistency using a MAC3D motion capture system (Motion Analysis Corp., Santa Rosa, CA, USA; 250 Hz) to determine agreement between the instance of the participant’s center of gravity and maximal knee flexion, with the instance of a switch from horizontal braking to horizontal propulsive force and the second peak of the vertical ground reaction force. Both vertical and horizontal braking impulses were determined as the time integration of the ground reaction force during the same period, from the moment of the initial heel strike until the moment the force time curve crosses the zero axis in the anterior–posterior waveform. All kinetic variables were normalized to body mass to account for inter-individual variability. Data processing and analysis were conducted using a custom MATLAB algorithm (R2021a, MathWorks Inc., Natick, MA, USA).

### 2.3. Data Processing and Outcome Measures

Touchdown and take-off were identified using a 20 N threshold in the vertical ground reaction force (GRF) from the filtered data. The horizontal reactive strength index  $RSI_{hor}$  was calculated for each individual hop as described by Sarabon et al. [5], as the ratio between hop distance by the preceding ground contact time (Equation (1)). Total  $RSI_{hor}$  for each trial was computed by dividing the total hop distance by the cumulative ground contact time across all hops.

$$\text{Reactive Strength Index Horizontal } (RSI_{hor}) = \left( \frac{\text{Hop Distance}}{\text{Ground Contact Time}} \right) \quad (1)$$

### 2.4. Statistical Analysis

Descriptive statistics, including means and standard deviations, were used to summarise central tendency and variability. Assumptions of univariate normality, outliers, and sphericity were assessed prior to inferential analysis. Outliers were identified through boxplot inspection, with data points exceeding three standard deviations (SD) from the mean manually excluded from further analysis. The Shapiro–Wilk test [18] was used to assess normality, complemented by Q-Q plot inspection for visual evaluation of kurtosis and skewness. Limb asymmetry between dominant and non-dominant legs was calculated using average trial data in Microsoft Excel (version 16.93.1; Microsoft Corp., Washington, DC, USA) following Equation (2) [1,19]. The magnitude of asymmetry was expressed as

a percentage by comparing the mean values of the dominant and non-dominant limbs. Paired *t*-tests were used to determine the statistical significance of these differences.

$$Asymmetry = \left[ \left( \frac{100}{Maximum\ Value} \right) \times (Minimum\ Value) \right] \times -1 + 100 \quad (2)$$

The direction of individual asymmetries was determined by using an IF function (\* IF (dominant limb/non-dominant limb, -1, 1)) as described by Davey et al. (2021) and used for further individual analysis [1].

### 3. Results

The means and standard deviations for all kinematic and kinetic data are detailed in Supplementary Tables S1 and S2. Asymmetries in kinematic data for the 3-Hop and 5-Hop protocols are summarized in Table 1. The average kinematic asymmetries were consistently below 7.1%, ranging from 0.00% to 28.9%, with RSI showing the greatest asymmetry. Large standard deviations were observed across all asymmetries, indicating high variability. The magnitude of these asymmetries varied across different kinematic parameters. Notably, greater flight times (0.629 to 1.81%) were observed in the non-dominant limb during all 5-Hop trials, contributing to longer hop durations for the non-dominant limb. However, across the forty kinematic variables, significant differences between limbs of averaged values were only seen in Flight Time (Hop 3) and Hop Time (Hop 2–3) ( $p < 0.05$ ) of 3-Hops which are both closely linked (Table S1). Averaged kinetic asymmetries ranged from 0.0% to 95.4%, with the largest asymmetries observed in the vertical and horizontal braking impulses and are summarized in Table 2. The magnitude of asymmetry in the kinetic variables varied across the 3-Hop phases. During the 5-Hop test, greater (31.5–51.8 N.kg) mean maximal vertical force values were consistently observed in the non-dominant limb across hops compared to the dominant limb (31.2–50.1 N.kg), whereas larger (0.833–0.370 Ns.kg) horizontal propulsive impulses were consistently observed in the dominant limb across all hops compared to the non-dominant limb (0.814–0.313 Ns.kg). Vertical braking impulses for both the 3-Hop and 5-Hop protocols were significantly greater for Hop 1 than subsequent hops (3-Hop:  $29.6 \pm 24.1\%$ ; 5-Hop:  $39.8 \pm 31.6\%$ ). The asymmetry between hops decreased by ~2% across subsequent hops, with reduced between-subject variability (11.2% to 15.6%, range: 0.0% to 53.8%). Vertical propulsive impulse asymmetries were consistent across the 3-Hop and 5-Hop protocols (7.77% to 15.4%, range = 0.0% to 61.6%), with minimal changes in asymmetry between hops (~1% to 2%). Notably, significantly greater variability was observed in the final hop for both the 3-Hop and 5-Hop protocols, inflating the mean values (3-Hop range: 0.0% to 47.5%; 5-Hop range: 0.75% to 61.6%), when compared to earlier hops (range: 0.0% to 31.0%). Horizontal braking impulse asymmetries decreased between each hop for the 3-Hop and 5-Hop protocols (38.8% to 19.9%), with a reduction in between-subject variability (range: 0.0% to 90.9%). A ~14%  $\Delta$  in asymmetry was observed between Hops 1–2 and Hops 2–3 in the 3-Hop protocol, and a ~4% to 11%  $\Delta$  was noted between hops in the 5-Hop protocol. In contrast, horizontal propulsive impulse asymmetries increased between hops for both protocols (10.4% to 17.6%). A ~44%  $\Delta$  in asymmetry was observed between Hops 1–2 and Hops 2–3 in the 3-Hop protocol, while the  $\Delta$  in asymmetry between hops in the 5-Hop protocol ranged from ~1% to 3%. Significant differences between limbs were only seen in Horizontal Propulsive Impulse (Hops 2–3) of the 3-Hops ( $p < 0.001$ ) and Hops 3–4 and Hops 4–5 in the 5-Hops ( $p < 0.05$ ).

**Table 1.** 3-Hop and 5-Hop mean asymmetry scores (%) ± standard deviations for hop kinematics.

Asymmetry Variable	3-Hop		5-Hop	
	Means ± SD (%)	Range (%)	Means ± SD (%)	Range (%)
<b>Flight Time</b>				
Hop 1	4.72 ± 3.85	0.00 to 14.3	4.63 ± 3.23	0.00 to 12.9
Hop 2	4.51 ± 3.38	0.00 to 11.8	6.31 ± 5.94	0.00 to 26.5
Hop 3	4.59 ± 3.92 *	0.00 to 14.0	6.18 ± 4.26	0.00 to 17.1
Hop 4			5.24 ± 3.98	0.00 to 17.1
Hop 5			4.34 ± 3.64	0.00 to 14.9
<b>Ground Contact Time</b>				
Hops 1–2	5.41 ± 3.92	0.00 to 16.7	4.77 ± 4.02	0.00 to 17.2
Hops 2–3	5.25 ± 3.41 *	0.00 to 14.3	5.09 ± 4.02	0.00 to 16.7
Hops 3–4			5.52 ± 4.42	0.00 to 17.9
Hops 4–5			4.58 ± 3.66	0.00 to 14.3
<b>Hops Times</b>				
Hops 1–2	3.41 ± 3.14	0.00 to 12.3	4.52 ± 2.95	0.00 to 11.3
Hops 2–3	3.49 ± 2.24	0.00 to 9.23	4.25 ± 2.79	0.00 to 10.5
Hop 3–4			3.83 ± 3.44	0.00 to 12.3
Hop 4–5			3.48 ± 2.75	0.00 to 13.0
Total Hop Time	2.39 ± 2.18	0.00 to 9.20	2.45 ± 1.62	0.00 to 6.29
<b>Hop Distance</b>				
Hop 1	3.67 ± 2.54	0.00 to 11.2	3.66 ± 3.27	0.00 to 12.6
Hop 2	3.04 ± 2.41	0.00 to 9.41	3.50 ± 3.16	0.00 to 12.7
Hop 3	3.18 ± 2.38	0.00 to 11.1	3.88 ± 2.35	0.40 to 10.1
Hop 4			4.01 ± 3.07	0.50 to 10.4
Hop 5			4.65 ± 3.19	0.00 to 11.9
Total Hop Distance	2.39 ± 1.89	0.18 to 10.6	3.32 ± 2.72	0.09 to 9.34
<b>Reactive Strength Index</b>				
Hops 1–2	5.45 ± 4.05	0.14 to 22.0	5.49 ± 4.86	0.00 to 25.8
Hops 2–3	6.26 ± 4.59	0.25 to 17.0	6.08 ± 5.92	0.13 to 28.9
Hops 3–4			7.07 ± 5.29	0.13 to 25.4
Hops 4–5			7.04 ± 4.56	0.33 to 18.5
Total RSI <sub>hor</sub>	4.87 ± 3.33	0.27 to 14.2	5.16 ± 4.29	0.08 to 20.5

Key: SD = Standard Deviation; Time variables = s; Distance variables = m; RSI = m.s<sup>-1</sup>; \* significant difference between limbs *p* < 0.05.

**Table 2.** 3-Hop and 5-Hop mean asymmetry scores (%) ± standard deviations for hop kinetics.

Asymmetry Variable	3-Hop		5-Hop	
	Means ± SD (%)	Range (%)	Means ± SD (%)	Range (%)
<b>Maximal Vertical Force</b>				
Hops 1–2	9.94 ± 7.87	0.15–33.9	8.06 ± 7.24	0.33–30.6
Hops 2–3	10.3 ± 7.53	0.07–29.1	10.4 ± 8.88	0.08–36.6
Hops 3–4			11.2 ± 8.70	0.96–28.3
Hops 4–5			11.5 ± 7.61	0.41–29.1
<b>Vertical Braking Impulse</b>				
Hops 1–2	29.6 ± 24.1	0.00–91.2	39.8 ± 31.6	0.00–95.4
Hops 2–3	14.3 ± 12.0	0.75–51.1	15.6 ± 12.4	0.78–53.8
Hops 3–4			13.5 ± 10.9	0.33–40.2
Hops 4–5			11.2 ± 8.96	0.00–30.8

**Table 2.** *Cont.*

Asymmetry Variable	3-Hop		5-Hop	
	Means ± SD (%)	Range (%)	Means ± SD (%)	Range (%)
Vertical Propulsive Impulse				
Hops 1–2	7.77 ± 5.95	0.45–25.6	8.93 ± 6.13	0.46–27.6
Hops 2–3	9.44 ± 8.87	0.00–47.5	7.96 ± 5.44	0.00–24.3
Hops 3–4			10.2 ± 7.15	0.32–31.0
Hops 4–5			15.4 ± 14.0	0.75–61.6
Horizontal Braking Impulse				
Hops 1–2	38.8 ± 26.0	0.00–90.9	32.4 ± 23.6	0.00–87.5
Hops 2–3	24.9 ± 16.6	0.00–72.7	36.9 ± 23.6	0.00–84.0
Hops 3–4			25.0 ± 14.2	0.00–61.3
Hops 4–5			19.9 ± 15.0	1.72–51.8
Horizontal Propulsive Impulse				
Hops 1–2	10.8 ± 7.07	0.00–28.4	10.4 ± 8.91	0.00–37.4
Hops 2–3	14.8 ± 9.30 †	0.00–34.0	11.8 ± 8.44	0.00–31.7
Hops 3–4			14.4 ± 9.82 *	0.00–42.2
Hops 4–5			17.6 ± 12.3 *	2.56–66.7

Key: SD = Standard Deviation; Force variables = Ns.kg; Impulse variables = Ns.kg; \* significant difference between limbs  $p < 0.05$ ; † significant difference between limbs  $p < 0.001$ .

An individualized analysis of 5-hop asymmetry, including both magnitude and direction, is presented in Table 3. Three subjects were selected based on their hop performance, representing the furthest, mean, and shortest 5-hop distances, respectively. While no consistent trend was observed in the direction of kinematic measures across the subjects, ground contact time and hop distance demonstrated limb-specific biases in subjects 2 and 3. Specifically, subject 2 exhibited a bias toward the dominant limb, whereas subject 3 showed a bias for the non-dominant limb. Kinetic measures did not reveal a consistent trend in limb dominance across subjects. However, subject 2 exhibited a dominant limb bias in both vertical braking and horizontal propulsive forces across the hops.

**Table 3.** 5-Hop asymmetry direction within individuals of varying 5-Hop success.

5-Hop Distance (Dom/Non/Mean) Variable	Subject 1 14.1 m/14.1 m/14.1 m Asymmetry/Direction	Subject 2 11.3 m/10.8 m/11.1 m Asymmetry/Direction	Subject 3 7.80 m/8.15 m/7.97 m Asymmetry/Direction
Hop Distance			
Hop 1	1.51%/non	3.80%/dom	7.30%/non
Hop 2	1.92%/dom	4.81%/dom	3.50%/non
Hop 3	1.40%/non	4.80%/dom	3.23%/non
Hop 4	1.67%/dom	2.08%/dom	7.00%/non
Hop 5	0.27%/dom	4.44%/dom	0.97%/non
Total Hop Distance	0.21%/dom	3.29%/dom	4.29%/non
Ground Contact Time			
Hops 1–2	3.85%/dom	6.67%/dom	9.68%/non
Hops 2–3	16.7%/dom	3.45%/dom	0.00%/n/a
Hops 3–4	4.35%/non	7.14%/dom	7.41%/non
Hops 4–5	4.76%/non	0.00%/n/a	10.7%/non

Table 3. Cont.

5-Hop Distance (Dom/Non/Mean) Variable	Subject 1 14.1 m/14.1 m/14.1 m Asymmetry/Direction	Subject 2 11.3 m/10.8 m/11.1 m Asymmetry/Direction	Subject 3 7.80 m/8.15 m/7.97 m Asymmetry/Direction
Vertical Braking Impulse			
Hops 1–2	57.0%/non	90.9%/dom	34.2%/dom
Hops 2–3	16.6%/dom	9.41%/dom	42.3%/dom
Hops 3–4	18.4%/non	0.37%/dom	31.7%/non
Hops 4–5	22.8%/non	0.30%/dom	28.3%/non
Horizontal Braking Impulse			
Hops 1–2	0.00%/n/a	0.00%/non	77.8%/non
Hops 2–3	80%/non	7.69%/non	50.0%/dom
Hops 3–4	56.5%/non	20.00%/dom	25.0%/dom
Hops 4–5	46.0%/non	2.44%/dom	29.0%/non
Vertical Propulsive Impulse			
Hops 1–2	11.2%/dom	0.78%/non	99.6%/non
Hops 2–3	1.78%/non	0.00%/n/a	43.4%/non
Hops 3–4	9.30%/dom	2.29%/dom	44.4%/dom
Hops 4–5	25.6%/dom	1.53%/dom	49.1%/dom
Horizontal Propulsive Impulse			
Hops 1–2	7.34%/dom	2.13%/dom	15.4%/dom
Hops 2–3	5.19%/non	14.3%/dom	5.66%/non
Hops 3–4	15.2%/dom	12.8%/dom	18.8%/non
Hops 4–5	28.3%/dom	21.1%/dom	6.25%/dom

Key: m = meters; non = non-dominant; dom = dominant.

#### 4. Discussion

Physiotherapists and strength and conditioning coaches commonly utilize multiple-hop movements to assess limb asymmetry, which serves as a key indicator of injury risk and plays an essential role in rehabilitation and return-to-play protocols. This research aimed to enhance the understanding of how 3-Hops and 5-Hops, and their associated asymmetries, could be used effectively in clinical and performance settings. Specifically, the aims were to determine: (1) the magnitude and direction of asymmetry; (2) whether kinematic and or kinetic variables were more sensitive to asymmetries; (3) whether vertical and horizontal asymmetries were comparable across hops; and (4) if the magnitude of asymmetry differed if a 3-Hop or 5-Hop was used. The main findings were as follows: (1) the averaged kinematic asymmetries were below 7.1%, and ranged from 0.00% to 28.9%, with the greatest asymmetries observed in the 5-Hop (hop 2–3) RSI, and individual asymmetries showed no consistent trend across variables; however, ground contact time and hop distance showed limb-specific biases in two of the three subjects; (2) the average kinetic asymmetries were under 39.8%, ranging from 0.00% to 95.4%, with the largest asymmetries found in vertical braking impulse (hop 1–2); (3) greater asymmetries were noted in braking (mean 14.3–38.8%, max 95.4%) rather than propulsive (mean 7.77–14.8%, max 66.7%) impulses; however, there was no evidence for an increase in asymmetry with greater stretch loads (i.e., hops 3–4) as hypothesized; and, (4) there was a great deal of individual variability across measures as evidenced by large ranges and standard deviations.

A primary aim of the study was to determine the magnitude of asymmetry in both the kinematics and kinetics of horizontal multiple-hops in series, specifically GRFs on embedded force platforms. Our findings were that average measures of kinematic asymmetry were <7.1% for both the 3-Hop and 5-Hop assessments, which were in agreement with previously reported kinematic asymmetries [1] as well as less than asymmetry thresholds

(10–15%) thought to affect performance or increase injury prevalence [20]. Davey et al. (2021) [1] reported mean asymmetries in kinematic variables of 3-Hop assessment ranging from 3.73 to 7.79% which aligned closely with our findings (2.39 to 5.25%). Whilst the RSI are not directly comparable given different computations (flight time vs. hop distance), the increases in RSI asymmetry observed by Davey et al. (2021) [1] between 3-Hops (~7.4 to 11.0%) were not reflected in our results (~5.5 to 6.3%), or for the 5-Hop assessment (~5.5 to 7.0%). The average kinetic asymmetries were substantially greater (<38.8%) than the kinematic asymmetries, with measures reaching as high as 95.4% observed in braking impulse variables. This is likely due to the variability associated with braking movement strategies and/or eccentric force capability [21], along with instantaneous fluctuations in mass-specific impulse. The direction of asymmetries observed for both kinetic and kinematic variables was non-uniform and consistent with previously reported studies [1,3,19,22,23], and individual analysis of both kinematic and kinetic data is justified.

Of interest to the authors was the magnitude of asymmetry associated with kinematic or kinetic variables. As intimated previously, kinetic variables are more sensitive to quantifying movement asymmetry, given that the averaged kinematic asymmetries were below 7.1% (ranging from 0.00% to 28.9%), whereas averaged kinetic asymmetries for 3-Hop and 5-Hop were as high as 38.8% (ranging from 0.00% to 95.4%). Similar kinetic asymmetries have been noted previously in horizontally oriented single-leg jump tasks. Bishop et al. (2021) noted individual asymmetries in peak force (~28%), eccentric impulse (~34%), and concentric impulse (~22%) for single-leg broad jumps [19]; however, not to the magnitude of those seen in this study, which makes sense given the higher stretch-loading associated with multiple-hops and in particular the fourth and fifth hops of a 5-Hop assessment [13]. Our findings support the work of Kotsifaki et al. (2021) who suggested that reporting the asymmetry associated with discrete outcome variables such as distance jumped does not adequately characterize the quality of the movement, and that movement strategy (kinetic) variables should be considered as they can give a fuller picture of hip-knee-ankle function in making decisions on return to play [10].

Additionally, it was of interest whether horizontal and vertical kinetic asymmetries were comparable across hops. When examining propulsive impulses, asymmetries were relatively similar between hops, with horizontal asymmetries being ~2–5% greater than vertical propulsive asymmetries, with this difference increasing with each successive hop. In contrast, horizontal braking impulses, except Hops 1–2, were ~10–20% greater than their vertical counterparts. To the authors' knowledge, no other researchers have examined asymmetries in this manner. Whether these differences can be explained in terms of physical or technical deficiencies is unknown; however, it may be that horizontal eccentric/braking capability was relatively untrained in this cohort. Alternatively, the effect of foot placement relative to the moving center of mass (COM) could have influenced braking forces more than vertical braking impulses. Interestingly, Kotsifaki et al. (2021) found that hop asymmetry in a cohort recovering from ACL reconstruction was more pronounced in the force generation/concentric phase rather than the force absorption/eccentric phase, which was not the case in this study, the physiological status of the respective cohorts no doubt explaining the differences [10]. Furthermore, Lloyd et al. (2020) concluded that 3-Hop distance masked the residual deficits in reactive strength performance, and our vertical and horizontal braking asymmetries certainly support such a contention [3].

It was hypothesized that the increased stretch-load demand of 5-Hop assessment would result in more significant asymmetries in the later hops. Regarding vertical and horizontal propulsive impulse, the actual asymmetry increased by ~7% across jumps. However, contrary to the hypothesis, no significant increase in asymmetries were observed

with greater stretch loads (i.e., hops 3–4); in fact, vertical and horizontal braking impulse asymmetry decreased by ~13 to 28% across hops, and therefore the hypothesis was rejected. Why this is the case is unclear, and since no other research group has examined the effect of stretch loading asymmetry, comparing our findings is problematic.

It is important to note the large standard deviations observed with some of the averaged asymmetry measurements, highlighting considerable within and intra-subject variability, underlying the importance of looking past the averaged data and more at individual results; this variability reported in previous studies [1,3,19]. The levels of variability seen in this study are incomparable to those seen in other multiple-hop studies, a phenomenon with this type of testing. Asymmetries higher than 95% were seen in braking impulses, and only comparable to those seen in kinetics of high velocity sprinting, but incidentally not statistically significant due to the high variability seen [24]. Previously, Bishop et al. (2022) [23] determined that the magnitudes of asymmetry were inconsistent across time points during a competition season; however, they also determined that limb dominance was consistent. It is conceivable that substantial shifts in limb dominance and magnitude are expected, within sessions and over time. The variability in movement strategy, both for propulsion and braking, mainly depends on the preceding hop strategy and is not independent of one another. Therefore, dominance could be influenced by, and frequently change based on, the variable being assessed and the task in question [15]. Regardless, this high variability likely precludes any meaningful between-group session comparisons, and our results would support other authors' suggestions to analyze symmetry data individually [3].

A limitation to this study was the utilization of a heterogeneous non-injured sample of male university-level athletes; therefore, generalizations of these results to other populations, such as females or those with lower limb injuries, must be made cautiously. Whilst every reasonable precaution was taken to ensure subjects were in a similar state of rest from physical training, this could not be guaranteed due to the varied nature of the sports involved. However, other researchers have suggested that this may not impact the magnitude and direction of asymmetry [1,23]. Further to this is the determination of dominance between limbs for limb-to-limb comparisons. In this study, dominance was determined by their 'kicking limb'; whilst this might be a rational approach and commonplace in other studies [15], this does not establish it as a 'stronger limb', or a better performing limb in hopping or other sports-related tasks [25], as this is highly individual. Further, there is the potential for this to further mask asymmetry due to quantification of dominance. In contrast, studies in injured cohorts have used affected or injury limb versus non-affected or uninjured limb in their classification [3,4,12].

## 5. Conclusion and Practical Application

This study enhances understanding of asymmetries in horizontally oriented hopping tasks by distinguishing between outcome (kinematic) and movement strategy (kinetic) factors. Multiple-hop tasks like the 3-Hop and 5-Hop offer more functionally relevant assessments of lower limb asymmetries than single hop tests, and should be prioritized by performance coaches for future training direction. While hop distance is a reliable outcome measure, it lacks detail on movement strategies, which could be key for identifying deficits, such as reduced eccentric braking capacity, that may increase injury risk and delay return-to-play.

To improve diagnostic value, practitioners should assess both outcomes and movement strategies concurrently, with particular attention given to distinguishing propulsive and braking mechanisms, as well as parsing horizontal and vertical components of motion. Individualized analysis is recommended over averaged data to better capture asymmetries. Given the minimal differences between 3-Hop and 5-Hop tests, using both may be

redundant. Accessible and largely cost-effective technologies like mobile video analysis and inertial sensors can provide further detail in the assessment of movement strategies. Future research should explore longitudinal designs in return-to-play populations and under fatigue conditions.

**Supplementary Materials:** The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/biomechanics5030067/s1>, Table S1: 3-Hop and 5-Hop kinematics descriptive data; Table S2: 3-Hop and 5-Hop kinetics descriptive data.

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## Abbreviations

The following abbreviations are used in this manuscript:

3-Hop	Triple-hop
5-Hop	Quintuple-hop
GCT	Ground contact time
RSI <sub>hor</sub>	Reactive Strength Index horizontal
GRF	Ground reaction force
COP	Center of pressure
COM	Center of mass

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