Asymmetry During Landing Impacts Following Jumps with Aerial Rotation in Collegiate Men's Basketball Players

John R. Harry[a*], Sunny Park[a], Michael Stewart [a], Mia Hite [a], Anton Simms [a], Margaret Larsen [a], Chris Bishop [b]

[a] Dept. of Kinesiology & Sport Management, Texas Tech University, Lubbock, TX 79409 USA
[b] London Sport Institute, Middlesex University, London NW4 4BT, UK

Declaration of Interest: The authors declare no competing interests.

Corresponding Author:
John R. Harry, PhD, CSCS
Department of Kinesiology & Sport Management, 3204 Main Street, Lubbock, TX, 79409 USA Email: john.harry@ttu.edu; Phone: 806-834-7836

Funding Details: The authors have no funding to declare. External resources did not support this project in the public, commercial, or not-for-profit sectors.

Running Title: Landing with Aerial Rotation

Abstract

This project explored whether a) landing performances and b) impact force asymmetries were different during countermovement jump (CMJ) landings with leftward versus rightward aerial rotation in 19 collegiate men's basketball players. Replicated single-subject analyses were performed to identify differences that were *both* statistically significant and important for *each* individual. CMJ landing performance and loading, attenuation, and control phase durations were compared, while interlimb vertical ground reaction forces (GRF) were compared during each phase of CMJ landings with leftward and rightward rotations, respectively, using the model statistic and coefficient of variation techniques. The model statistic provided random chance probability (α = 0.05). The coefficient of variation provided whether differences exceeded the largest amount of variation from each limb or rotation direction. The bilateral asymmetry index (BAI; difference between dominant and non-dominant limbs divided by sum of the two limbs) was also calculated. Statistically significant (model statistic results) and important (coefficient of variation results) differences in landing performance were detected between rotation conditions in four participants. Most participants did not display significant and important asymmetries for the changes of vertical GRF during any phase of CMJ landings with leftward nor rightward rotations. Large amounts of intra-individual variation seem to be an influential factor for these results, as basketball players seem to have unrefined landing strategies that could require targeted training. Because the BAI values reached as high as ± 531% without coinciding with significant and important asymmetry, researchers and practitioners may need to reevaluate the way in which asymmetry indices are interpreted.

Keywords: Impact force; control; loading; attenuation; land

Word Count: 5,093

INTRODUCTION

The countermovement jump (CMJ) is a physical task that involves a vertical jump and subsequent landing (32). CMJ performance is critical in most sports, notably basketball (14). This is because basketball players perform as many as 60 CMJs per game (30), both with and without the ball (12). While CMJ performance is largely associated with jumping output (9, 17, 23, 24, 27, 29), the landing phase of the CMJ is also critical due to its association with the relatively high rate of lower body injuries in basketball players (13, 31). Ultimately, there is a need for additional assessments of CMJ landings to obtain a more well-rounded understanding of basketball players' physical abilities and provide basketball practitioners with a working hypothesis to shape their own assessments, training, or both.

Many CMJ landings performed during basketball competitions involve an aerial rotation prior to returning to the ground. Prime examples of this include players jumping to secure a rebound and turning in the air to protect the ball from an opponent or jumping to block an opponent's shot and turning in the air to appropriately position their body for continued gameplay upon landing. While CMJ landings following an aerial rotation have received some attention in other sports, such as soccer (19), it remains unexplored in basketball players. What is known is that athletes apply unique inter-limb forces into the ground to cause their total body center of mass (COM) to rotate their body around the longitudinal axis (i.e., spin) when airborne (1). Upon ground contact, athletes again apply unique inter-limb forces to terminate the rotation of total body COM (19). Although moderate magnitude differences (Cohen's $d = 0.67$) have been shown between leftward and rightward change of direction performances in basketball players (37), performance differences have yet to be explored during CMJ landings with leftward versus rightward rotation in the population. While it is reasonable to expect basketball players to display different CMJ landing performances between leftward versus rightward aerial rotation, this working hypothesis warrants investigation.

Asymmetrical force production occurs during the jumping portion of conventional rotation-free CMJs in basketball players (24). Those asymmetries are likely to continue throughout the landing, and can even increase in magnitude (11). This is an important consideration for CMJ landings with aerial rotation, as the magnitudes of each limb's vertical impact forces, which have historically been linked with overuse musculoskeletal injury risk (15), could be uniquely affected by the need to perform a leftward versus rightward aerial rotation. For instance, athletes must redirect some of the bilateral impact forces along the anterior-posterior axis to terminate rotation (19). As those impact forces vary in magnitude and direction between the limbs, they could coincide with unique vertical impact forces between limbs. Ultimately, asymmetrical impact forces during CMJ landings, regardless of rotation demands, might motivate practitioners to make important decisions regarding athletic potential, overuse injury risk, or training requirements. If worsened performance and alarming impact force asymmetries occur during CMJs with an aerial rotation to a specific direction, additional considerations may be required prior to making important decisions about an athlete's needs.

The purpose of the study was two-fold. First, we sought to determine whether landing performances are different during CMJs with leftward versus rightward aerial rotation. We hypothesized that landing performance would be different between rotation directions in most participants. Second, we sought to determine whether impact force attenuation asymmetries would occur during each rotation direction, which we hypothesized to be true for most participants.

METHODS

Experimental Approach to the Problem

We determined whether a) landing performances and b) impact force asymmetries were different during CMJs with leftward versus rightward aerial rotation in collegiate men's basketball players. To do this, we performed a replicated single-subject analysis using a recently recommended approach for team sport samples (21). This approach combines tests results from the model statistic (3) and a comparison between the percent difference relative to the coefficient of variation (7). Thus, test results determined the number of players displaying differences that were both statistically significant and important for *each* individual as opposed to the sample's "average" player. We supplemented the test results with a common asymmetry assessment, the bilateral asymmetry index (BAI).

Subjects

A convenience sample of 19 participants were evaluated in this study. Participant age, height, body mass, limb dominance, and primary playing position information is provided in Table 1. All were active members of a NCAA Division 1 men's basketball program at their time of testing and free of any injury, condition, or ailment that would have limited their ability to perform various CMJ movements. Prior to completing any laboratory activities, written informed consent was provided to the investigators in accordance with the university Institutional Review Board at the site of data collection and the Declaration of Helsinki. All testing took place in June, prior to formalized longitudinal training for the upcoming season.

< Insert Table 1 About Here >

Procedures

Participants completed all tests during a single laboratory visit. Age, height, body mass, and primary playing position were recorded, while the dominant limb was verbally provided to the researchers as defined as the limb they would use to kick a ball (10). Participants completed a dynamic warm-up under the direction of their strength and conditioning coach. This warm-up was specific to each athlete's requirement to adequately prepare for physical activity, and therefore, a standardized warmup was not provided to the players. Following the warm-up, participants were provided with a demonstration of the CMJ tasks after which up to five practice trials were performed for familiarization with the experimental tasks and the laboratory environment. All jump trials were performed on two three-dimensional force platforms (OPT464508; Advanced Mechanical Technology, Inc., Watertown, MA, USA) mounted flush with the floor and sampled at 1000 Hz. The CMJ task was performed with participants starting in a standing still position with their feet position at approximately hip width and arms at their side. Participants then initiated the movement by performing a countermovement with a self-selected depth and arm swing before jumping upwards and reaching both hands vertically, aiming to jump as high as possible as quickly as possible. The CMJ was completed by landing on the force platforms and terminating downward momentum as quickly as possible before returning to a standing position. The aerial rotations consisted of a 90-degree turn about the longitudinal axis in both the leftward and rightward directions. Because related work showed that CMJs with rotation are initiated before takeoff (1), we did not want to compromise athletes' strategies to create rotation by providing specific instructions. Thus, no instructions were provided for when to start the rotation (i.e., at take-off, after take-off, etc.), only that the rotation must be 90 degrees to a specific side. Thus, participants started the task in the standing position with both feet on the same force platform and landed with each foot on its own force platform. Three trials were recorded for each task, for a total of six recorded trials.

Data Processing

Raw GRF signals were processed in Visual3D (HAS-Motion, Inc., Kingston, ON). First, a 4th order low pass Butterworth digital filter with a cutoff frequency of 50 Hz was applied to the raw GRF signals to remove high frequency noise to more accurately detect key events without compromising the magnitudes of the dependent variables (20). The filtered vertical GRF signals from the two force platforms were summed to create a vertical GRF representative of total body COM. From the summed vertical GRF, vertical COM acceleration was calculated using Newton's law of acceleration ($a = \sum F/m$), and vertical COM velocity was calculated as the cumulative time-integral of the acceleration data using the trapezoidal rule.

The jumping portion of the CMJ was not examined here as it was not part of the study purpose. To deconstruct the landing portion of the CMJ into key phases (Figure 1), takeoff and ground contact were identified as the instants when the summed vertical GRF data decreased below and subsequently increased above 20 N, respectively. The end of the landing was defined as the time when the vertical COM velocity crossed zero after ground contact, as this time represents the termination of downward motion. Ground contact defined the start of the loading phase, and the end of the phase was defined by the global maximum vertical GRF (18, 19). The end of the loading phase defined the start of the attenuation phase, which ends at the time of the local minimum vertical GRF. This is different than previous definitions of the attenuation phase that defined its end as the end of downward motion (18). We feel this is an improvement because attenuation is defined as "a lessening in amount of force, magnitude, or value" (33) and the vertical GRF often decreases and increases between the global maximum and the end of downward motion, as shown in Figure 1. The final phase of landing, called the control phase, was defined between the end of the attenuation phase and the end of downward motion. The time durations of each phase and the overall landing were extracted, as were the phase-specific changes of vertical GRF from both limbs. The vertical GRF values were scaled to participant body weight. Landing performance was assessed using the landing performance index, or LPI, which is the ratio of jump-landing height and the time to complete the landing (22). As LPI is a ratio, we secondarily assessed landing performance using jump-landing height and landing time to help explain why LPI did or did not change.

< Insert Figure 1 About Here >

Statistical Analysis

Mean and standard deviation values were calculated across trials per limb per participant. Due to the current sample consisting of high-level athletes and the documented importance of assessing the individual (2, 26, 38), we chose to analyze data at the individual level through parallel interpretation from the model statistic and coefficient of variation (21). Specifically, the model statistic was used to determine whether the difference between two means was due to random chance (i.e., not statistically significant), using a critical value of 1.6533 for 3 trials used to obtain each mean and a 5% alpha level (3). The coefficient of variation was used to determine whether the difference between two means was important or trivial based on whether the difference between means exceeded the greatest amount of variation observed across the trials used to obtain each mean (4). For landing performance and phase durations, comparisons were made between rotation directions (i.e., leftward vs rightward).

For inter-limb differences, vertical GRF metrics were compared between the left and right limbs during the leftward and rightward rotations directions, respectively. Only changes associated with a significant *and* important difference were considered meaningful for interpretation. Although inter-limb differences are often assessed in full using symmetry indices (6, 7), we supplemented the model statistic and coefficient of variation procedures with a symmetry index. Our purpose for this approach was to help researchers and practitioners determine whether inter-limb differences *might* be valuable when only using asymmetry indices. According to recommendations for bilateral tests (7), this was done using the BAI, which is calculated as the difference between the dominant and non-dominant limbs divided the sum of the two limbs multiplied by 100 to obtain a percent value (28). Positive BAI values indicate the participant favored the dominant limb and negative indices indicated favoring the non-dominant limb.

RESULTS

The LPI, landing height, and landing time data are presented in Figure 2. The difference in LPI between leftward and rightward rotations was statistically significant and important in four participants (participants 2, 6, 8, 17), with all four exhibiting better performance during leftward versus rightward rotations. Participants 4 and 9 displayed statistically significant and important increases in landing height during leftward versus rightward rotations. Participants 9 and 15 displayed statistically significant and important decreases in landing time during rightward versus leftward rotations.

Phase Durations

The loading, attenuation, and control phase durations are presented in Figure 3. Participant 8 displayed a statistically significant and important decrease in loading time during rightward versus leftward rotations. Participants 8, 11, and 18 displayed statistically significant and important decreases in attenuation time during rightward versus leftward rotations.

Participants 4, 9, and 14 displayed statistically significant and important decreases in control time during rightward versus leftward rotations.

< Insert Figures 2 & 3 About Here >

Loading Phase Asymmetry

The changes in vertical GRF for each limb during the loading phase along with the BAI values are presented in Figure 4. When performing the CMJ with leftward rotation, participants 5 and 9 displayed a statistically significant and important increase in the change of vertical GRF in the right versus left limb during the loading phase. The BAI for participant 5 was ~20% in favor of the non-dominant limb, while the BAI for participant 9 was ~22% in favor of the dominant limb. None of the participants displayed a statistically significant and important asymmetry during rightward rotations despite BAI values reaching ~60%.

< Insert Figure 4 About Here >

Attenuation Phase Asymmetry

The changes in vertical GRF for each limb during the attenuation phase along with the BAI values are presented in Figure 5. During CMJs with leftward rotation, participants 5 and 12 displayed a statistically significant and important increase in the change of vertical GRF in the left versus right limb during the loading phase. Both of those participants had BAI values of ~20% in favor of the non-dominant limb. During CMJs with rightward rotation, participant 17 was the only one to display a statistically significant and important difference, with greater vertical GRF attenuation in the non-dominant versus dominant limb with a BAI of ~216%.

< Insert Figure 5 About Here >

Control Phase Asymmetry

The changes in vertical GRF for each limb during the control phase along with the BAI values are presented in Figure 6. During CMJs with leftward rotation, no participant displayed a statistically significant and important asymmetry in the change of vertical GRF during the control phase, even though BAI values reached approximately ± 530%. During CMJs with rightward rotation, only participant 2 displayed a statistically significant and important difference in the change of vertical GRF between limbs during the control phase, with a greater reduction of vertical GRF in the left versus right limb and a BAI of ~88%.

< Insert Figure 6 About Here >

DISCUSSION

The results of this study did not support our first hypothesis, as the difference in LPI between CMJs with leftward versus rightward rotations was statistically significant and important in only four of the 19 participants (~21%). Interestingly, none of those four participants exhibited statistically significant and important differences between rotation conditions for the component parts of LPI, landing height and landing time. In addition, none of the participants with statistically significant and important differences in landing height nor landing time were among the four participants with differences in LPI. When looking more deeply into the landing time results, it is apparent that some participants performed one or more phases more quickly and other phases more slowly during leftward and rightward conditions, but the changes in phase durations were not consistent from phase to phase. From a practical perspective, these results suggest that a significant and important difference in LPI cannot be assumed to coincide with a significant and important difference in landing height, landing time, phase times, or a combination thereof. Thus, an athlete could display a significant and important improvement in landing height or landing time alone but not display more “explosive” CMJ landings. This emphasizes the need to explore ratio-based metrics in parallel to its component parts.

The results of this study did not support our second hypothesis, as most participants did not display significant and important differences between limbs in the change of vertical GRF during any phase of CMJ landings with leftward nor rightward rotations. In addition, there was no consistency among phases for any participant displaying a significant and important difference in the change of vertical GRF between limbs in any phase. The lack of consistency suggests changes in vertical impact force during any individual phase, regardless of whether it be changing how impact is received, attenuated, or controlled, are not linked to changes in landing performance. This seems to be influenced by the relatively large amounts of variation across trials for each limb per participant, as evidenced by the magnitudes of the standard deviations. Variation of this kind is connected to strategy selection, which is influenced by previous experiences, task expectations, perceptions, and environmental and physical constraints (16).

One interpretation related to strategy is that lesser variation could indicate increased overuse injury risk because of greater conscious control and reduced movement automaticity (39). Reduced automaticity accentuates inhibitory mechanisms, constrained movement patterns, and altered force attenuations during landing (34). Conversely, one could hypothesize that athletes would be at a generally lower risk for overuse injury during landing when not constraining their options to a few landing strategies. Instead, greater variation across trials would represent athletes selecting trial-specific strategies from a larger pool. However, we consider the large variation across trials in each metric as a reflection of the athletes having unrefined landing strategies rather than an over-reliance on a few strategies nor retaining an overabundance of strategies. This is because strategies are learned over a sufficient period, and as a result, heavily influenced by training. For instance, when these results are compared to limb-specific jumping metrics extracted from a similar sample of collegiate men's basketball players (24), there is lesser variation across trials during jumping than landing. This, combined with our experiences working with collegiate basketball players, suggests that basketball players are trained in ways that help them refine their jumping strategies more so than their landing strategies, which warrants consideration when designing physical training programs. This could be an important training consideration or rationale for follow-up work, as prior work suggests that there could be a relationship between joint kinetic variability during landing and overuse injury proneness (25).

Perhaps the most intriguing result of this study was the BAI percentages. Our interpretation from these percentages is that basketball players likely have unrefined landing strategies. This conclusion aligns with previous research demonstrating a relationship between greater symmetry and training status or task familiarity, but the relationship had little effect on economy or energy expenditure (36). As mentioned previously, BAI is an index related to inter-limb asymmetry. A fairly recent systematic review suggests researchers consider asymmetries greater than ±15% as an indicator of greater injury risk and recommend asymmetries < ±10% for return to sport, though these values appear to have been arbitrarily chosen (8). If we use only the ±15% threshold for each change of vertical GRF metric, ~61% of BAI values (70 of 114) exceeded the threshold independent of whether the comparison between limbs was statistically significant, important, or both. Thus, overuse musculoskeletal injury risk connected to impact forces during the loading, attenuation, and control phases is quite high for most of these participants. This might also suggest a need to reconsider the use of arbitrarily selected blanket thresholds for asymmetry, especially during landing. In this sample, the BAI values for participants with significant and important differences in the change of vertical GRF between limbs, regardless of rotation direction was ± 21% for the loading phase, ± 215% for the attenuation phase, and ± 87% for the control phase. The largest BAI participant values regardless of whether there was a significant and important difference in the change of vertical GRF between limbs, irrespective of rotation direction, were ± 75% for the loading phase, ± 215% for the attenuation phase, and ± 531% for the control phase. Ultimately, these results suggest a glaring need to reevaluate the way in which asymmetry is assessed for practical importance when using asymmetry indices.

Before making training changes to address any unrefined strategies, practitioners should assess athletes' training history. This is because the CMJ landing with rotation assessed here was a bilateral jump with rotation followed by a bilateral landing. This type of jump-landing action may not be as familiar of a movement pattern for basketball players compared to other jump-landings, such as a one-foot approach takeoff with rotation followed by a 'one-two' landing. It is reasonable to presume that a lack of performance familiarity contributed to the variability in landing strategy. Additional repetitions of CMJ landings following aerial rotation may reduce variations without needing major training modifications.

A potential limitation of the current study was the absence of test-retest reliability. The dependent variables' reliability requires data be obtained using repeated measures testing. While that was not done here, previous work, supported by the current data, emphasizes the fact that repeated measures must be included when seeking to determine basketball players' consistency with respect to the magnitude, direction, or both, of impact force asymmetry (5, 40). Another possible limitation was the limited familiarity trials allotted to the sample. A greater number of trials could have helped these players become more accustomed to the laboratory controlled CMJ landings with rotation. There is also a potential influence from asymmetries during the jumping action of the CMJ on the magnitude of asymmetries during the landing portion. While it was not an objective here, follow up work might consider exploring the contribution of jumping mechanics to landing mechanics. Lastly, data were collected during the first week of hands-on team activities, suggesting a potentially limited jump-landing ability as compared to that which could result from longitudinal training.

PRACTICAL APPLICATIONS

The data herein reinforces previous literature related to the need to assess individual landing asymmetry results before generalizing athletes or participants as a group (35). As asymmetry is a popular topic to focus on in training and testing, coaches and practitioners cannot rely on commonly used thresholds to indicate an important asymmetry. In fact, coaches and practitioners might need to eliminate asymmetry indices all together, or at minimum, consider them alongside probability tests, to determine the effects of asymmetry on performance or overuse injury risk. From a training perspective, there needs to be a greater emphasis on bilateral landing ability in this population. This is because the current players' unrefined landing strategies suggest the larger population of basketball players does not have a consistent solution for bilateral landing when a jump with aerial rotation is required. Although bilateral landings with or without aerial rotation may be less common rotation-free vertical jump-landings during training and testing, our results suggest landings following rotation should be treated as a necessary skill requiring training and monitoring.

Acknowledgements

The authors would like to thank each student-athlete who volunteered their time to participate in this project. There is no funding to declare. This work was not supported by any resources from the commercial, private, or not-for-profit sectors.

References

1. Barker LA, Harry JR, Dufek JS, and Mercer JA. Aerial Rotation Effects on Vertical Jump Performance Among Highly Skilled Collegiate Soccer Players. *The Journal of Strength & Conditioning Research* 31(4): 932-938, 2017.
2. Bates BT. Single-subject methodology: an alternative approach. *Medicine & Science in Sports & Exercise* 28: 631-638, 1996.
3. Bates BT, Dufek JS, and Davis HP. The effect of trial size on statistical power. *Medicine & Science in Sports & Exercise* 24: 1059-1065, 1992.
4. Bishop C, Abbott W, Brashill C, and Read P. Effects of Strength Training on Bilateral and Unilateral Jump Performance, and the Bilateral Deficit in Premier League Academy Soccer Players. *UK Strength and Conditioning Association* Published ahead of print, 2021.
5. Bishop C, Abbott W, Brashill C, Turner A, Lake J, and Read P. Bilateral vs. unilateral countermovement jumps: Comparing the magnitude and direction of asymmetry in elite academy soccer players. *The Journal of Strength & Conditioning Research* 36: 1660-1666, 2022.
6. Bishop C, Read P, Chavda S, and Turner A. Asymmetries of the lower limb: The calculation conundrum in strength training and conditioning. *Strength & Conditioning Journal* 38: 27-32, 2016.
7. Bishop C, Read P, Lake J, Chavda S, and Turner A. Interlimb asymmetries: understanding how to calculate differences from bilateral and unilateral tests. *Strength & Conditioning Journal* 40: 1-6, 2018.
8. Bishop C, Turner A, and Read P. Effects of inter-limb asymmetries on physical and sports performance: a systematic review. *Journal of Sports Sciences* 36: 1135-1144, 2018.
9. Chalitsios C, Nikodelis T, Panoutsakopoulos V, Chassanidis C, and Kollias I. Classification of Soccer and Basketball Players' Jumping Performance Characteristics: A Logistic Regression Approach. *Sports* 7: 163, 2019.
10. Chowning L, Krzyszkowski J, Nunley B, Lanier R, Gonzales I, Calamoneri T, Duffy A, and Harry JR. Biomechanical comparison of dominant and non-dominant limbs during leap-

landings in contemporary style female dancers. *Journal of Dance Medicine & Science* 25: 231-237, 2021.

11. Cone SM and Lee S. Lower limb force asymmetries during landing and jumping exercises: A pilot study. *International Journal of Exercise Science* 14: 544, 2021.
12. Conte D, Favero TG, Lupo C, Francioni FM, Capranica L, and Tessitore A. Time-motion analysis of Italian elite women's basketball games: individual and team analyses. *The Journal of Strength & Conditioning Research* 29: 144-150, 2015.
13. Cumps E, Verhagen E, and Meeusen R. Prospective epidemiological study of basketball injuries during one competitive season: ankle sprains and overuse knee injuries. *Journal of Sports Science & Medicine* 6: 204, 2007.
14. Drinkwater EJ, Pyne DB, and McKenna MJ. Design and interpretation of anthropometric and fitness testing of basketball players. *Sports Medicine* 38: 565-578, 2008.
15. Dufek JS and Bates BT. Biomechanical factors associated with injury during landing in jump sports. *Sports Medicine* 12: 326-337, 1991.
16. Dufek JS, Bates BT, Stergiou N, and James CR. Interactive effects between group and single-subject response patterns. *Human Movement Science* 14: 301-323, 1995.
17. Gonzalez AM, Hoffman JR, Rogowski JP, Burgos W, Manalo E, Weise K, Fragala MS, and Stout JR. Performance changes in NBA basketball players vary in starters vs. nonstarters over a competitive season. *The Journal of Strength & Conditioning Research* 27: 611-615, 2013.
18. Harry JR, Barker LA, Eggleston JD, and Dufek JS. Evaluating performance during maximum effort vertical jump landings. *Journal of Applied Biomechanics* 34: 403-309, 2018.
19. Harry JR, Barker LA, Mercer JA, and Dufek JS. Vertical and Horizontal Impact Force Comparison During Jump-Landings With and Without Rotation in NCAA Division 1 Male Soccer Players. *The Journal of Strength & Conditioning Research* 31(7): 1780-1786, 2017.
20. Harry JR, Blinch J, Barker LA, Krzyszkowski J, and Chowning L. Low pass filter effects on metrics of countermovement vertical jump performance. *The Journal of Strength & Conditioning Research* 36: 1459-1467, 2022.

21. Harry JR, Hurwitz J, Agnew C, and Bishop C. Statistical tests for sports science practitioners: Identifying performance gains in individual athletes. *The Journal of Strength & Conditioning Research* Epub Ahead of Print, 2023.

22. Harry JR, Simms A, and Hite M. Establishing phase definitions for jump and drop landings and an exploratory assessment of performance-related metrics to monitor during testing. *The Journal of Strength & Conditioning Research* 38: e62-e71, 2024.

23. Heishman A, Brown B, Daub B, Miller R, Freitas E, and Bemben M. The influence of countermovement jump protocol on reactive strength index modified and flight time: contraction time in collegiate basketball players. *Sports* 7: 37, 2019.

24. Heishman A, Daub B, Miller R, Brown B, Freitas E, and Bemben M. Countermovement jump inter-limb asymmetries in collegiate basketball players. *Sports* 7: 103, 2019.

25. James CR, Dufek JS, and Bates BT. Effects of injury proneness and task difficulty on joint kinetic variability. *Medicine & Science in Sports & Exercise* 32: 1833-1844, 2000.

26. Kinugasa T, Cerin E, and Hooper S. Single-subject research designs and data analyses for assessing elite athletes' conditioning. *Sports Medicine* 34: 1035-1050, 2004.

27. Kipp K, Kiely M, Giordanelli M, Malloy P, and Geiser C. Joint-and subject-specific strategies in male basketball players across a range of countermovement jump heights. *Journal of Sports Sciences*: 1-6, 2020.

28. Kobayashi Y, Kubo J, Matsubayashi T, Matsuo A, Kobayashi K, and Ishii N. Relationship between bilateral differences in single-leg jumps and asymmetry in isokinetic knee strength. *Journal of Applied Biomechanics* 29: 61-67, 2013.

29. Krzyszkowski J, Chowning LD, and Harry JR. Phase-specific predictors of countermovement jump performance that distinguish good from poor jumpers. *The Journal of Strength & Conditioning Research* 36: 3352-3358, 2022.

30. McInnes S, Carlson J, Jones C, and McKenna MJ. The physiological load imposed on basketball players during competition. *Journal of Sports Sciences* 13: 387-397, 1995.

31. McKay G, Goldie P, Payne W, Oakes B, and Watson L. A prospective study of injuries in basketball: a total profile and comparison by gender and standard of competition. *Journal of Science and Medicine in Sport* 4: 196-211, 2001.

32. McMahon J, Suchomel TJ, Lake J, and Comfort P. Understanding the key phases of the countermovement jump force-time curve. *Strength & Conditioning Journal* 40: 96-106, 2018.

33. Merriam-Webster (n.d.). Attenuation. In Merriam-Webster.com dictionary. 2023.

34. Nordin AD and Dufek JS. Load Accommodation Strategies and Movement Variability in Single-Leg Landing. *Journal of Applied Biomechanics*: 1-25, 2017.

35. Schot PK, Bates BT, and Dufek JS. Bilateral performance symmetry during drop landing: a kinetic analysis. *Medicine & Science in Sports & Exercise* 26: 1153-1159, 1994.

36. Seminati E, Nardello F, Zamparo P, Ardigò LP, Faccioli N, and Minetti AE. Anatomically asymmetrical runners move more asymmetrically at the same metabolic cost. *PLoS One* 8: e74134, 2013.

37. Versic S, Pehar M, Modric T, Pavlinovic V, Spasic M, Uljevic O, Corluka M, Sattler T, and Sekulic D. Bilateral symmetry of jumping and agility in professional basketball players: Differentiating performance levels and playing positions. *Symmetry* 13: 1316, 2021.

38. Ward P, Coutts AJ, Pruna R, and McCall A. Putting the "I" back in team. *International Journal of Sports Physiology and Performance* 13: 1107-1111, 2018.

39. Wulf G, McNevin N, and Shea CH. The automaticity of complex motor skill learning as a function of attentional focus. *The Quarterly Journal of Experimental Psychology: Section A* 54: 1143-1154, 2001.

40. Xu J, Jordan MJ, Chavda S, Turner A, and Bishop C. Test–Retest Reliability of the Magnitude and Direction of Asymmetry in the Countermovement Jump, Drop Jump, and Countermovement Rebound Jump. *Symmetry* 15: 1960, 2023.

Tables

Table 1. Participant demographics

Participant	Age (y)	Height (m)	Mass (kg)	Position	Dominant Limb
1	19	1.91	86.27	G	L
2	19	1.98	93.82	F	R
3	19	2.08	92.27	C	R
4	19	1.98	88.18	G	R
5	23	1.96	100.00	G	R
6	20	1.91	80.45	G	R
7	22	2.06	111.36	F	R
8	21	1.91	78.64	G	R
9	23	2.08	88.64	C	L
10	23	1.96	92.27	G	R
11	18	2.03	102.27	F	R
12	23	2.03	100.91	F	R
13	18	1.96	86.36	G	R
14	20	1.93	91.82	G	R
15	20	1.91	88.64	G	R
16	18	1.98	90.91	G	L
17	21	1.91	81.36	G	R
18	17	1.93	86.36	G	R
19	20	2.01	98.64	G	R
Group	20 ± 2	1.97 ± 0.06	91.54 ± 8.27	-	-

Figure Captions

Figure 1. Loading, Attenuation, and Control Phases of Landing as defined using vertical ground reaction forces and vertical center of mass velocity.

Notes – GRF: ground reaction force.

Figure 2. Landing Performance Indices, Landing Heights, and Landing Times for Each Participant during Landings with Leftward and Rightward Rotation.

Figure 3. Loading, Attenuation, and Control Phase Durations for Each Participant During Landings with Leftward and Rightward Rotation.

Figure 4. Limb-Specific Changes in Vertical Ground Reaction Force and the Corresponding Bilateral Asymmetry Indices for Each Participant During the Loading Phase of Landings with Leftward and Rightward Rotation.

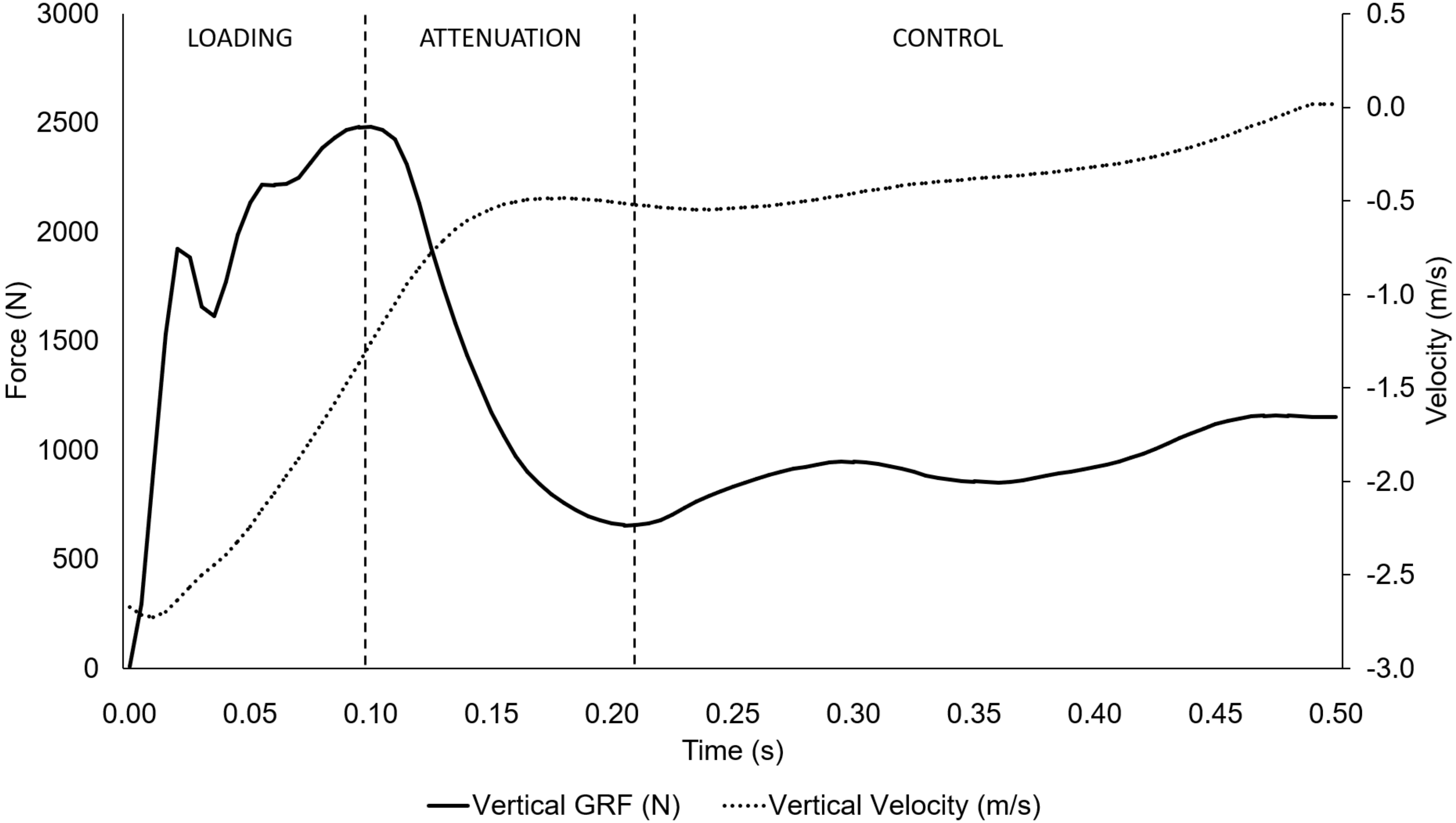
Notes – GRF: ground reaction force; BAI: Bilateral Asymmetry Index.

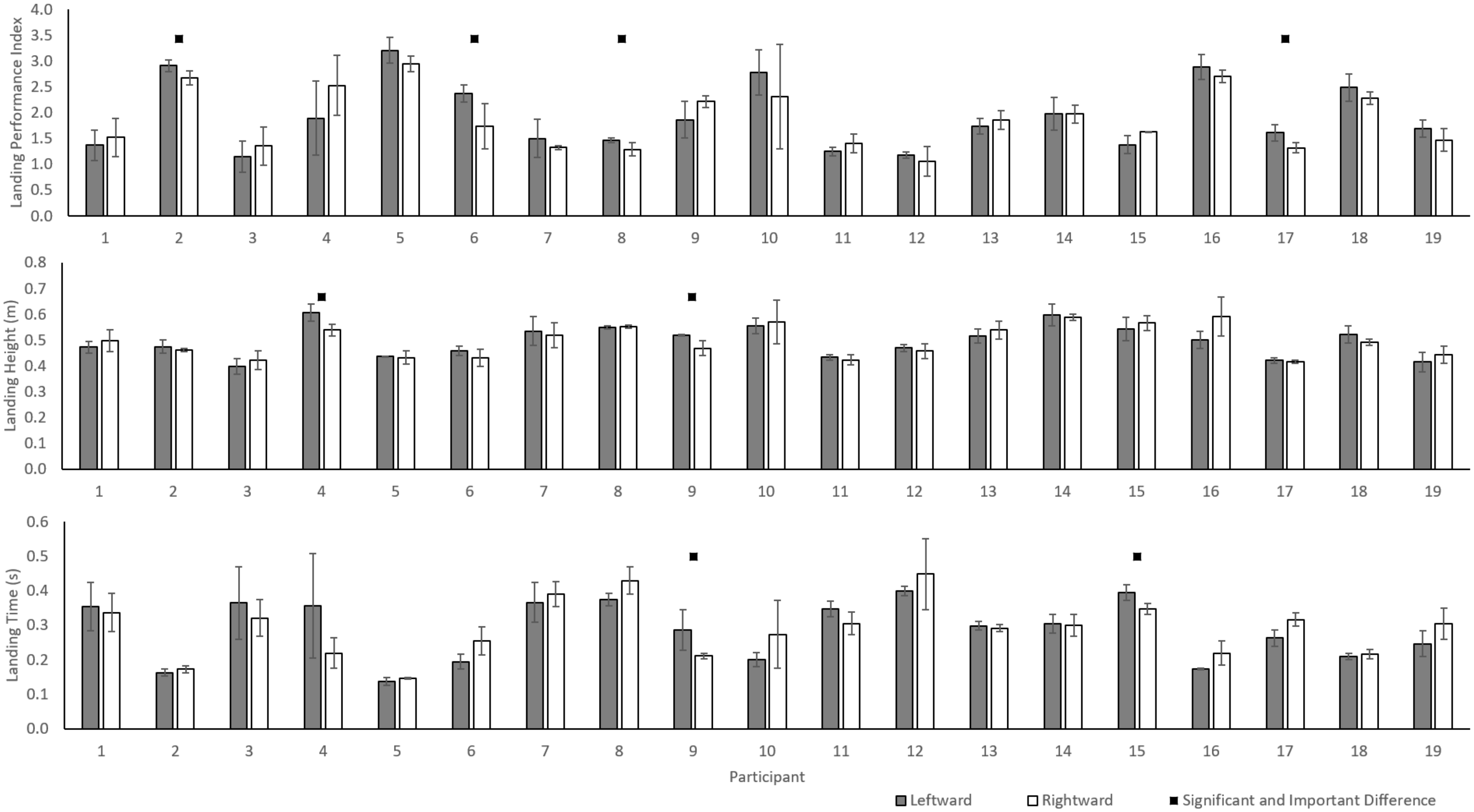
Figure 5. Limb-Specific Changes in Vertical Ground Reaction Force and the Corresponding Bilateral Asymmetry Indices for Each Participant During the Attenuation Phase of Landings with Leftward and Rightward Rotation.

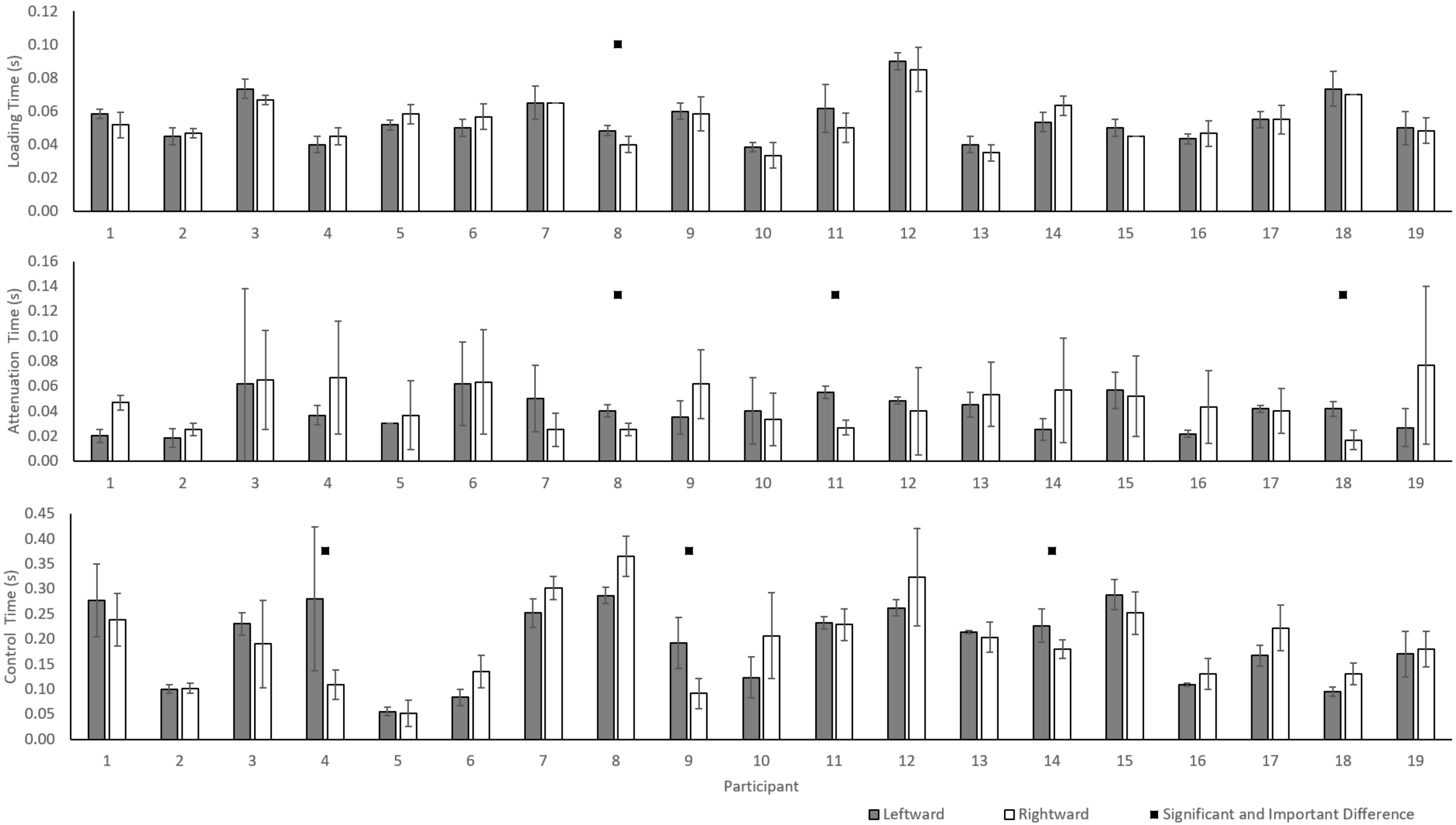
Notes – GRF: ground reaction force; BAI: Bilateral Asymmetry Index.

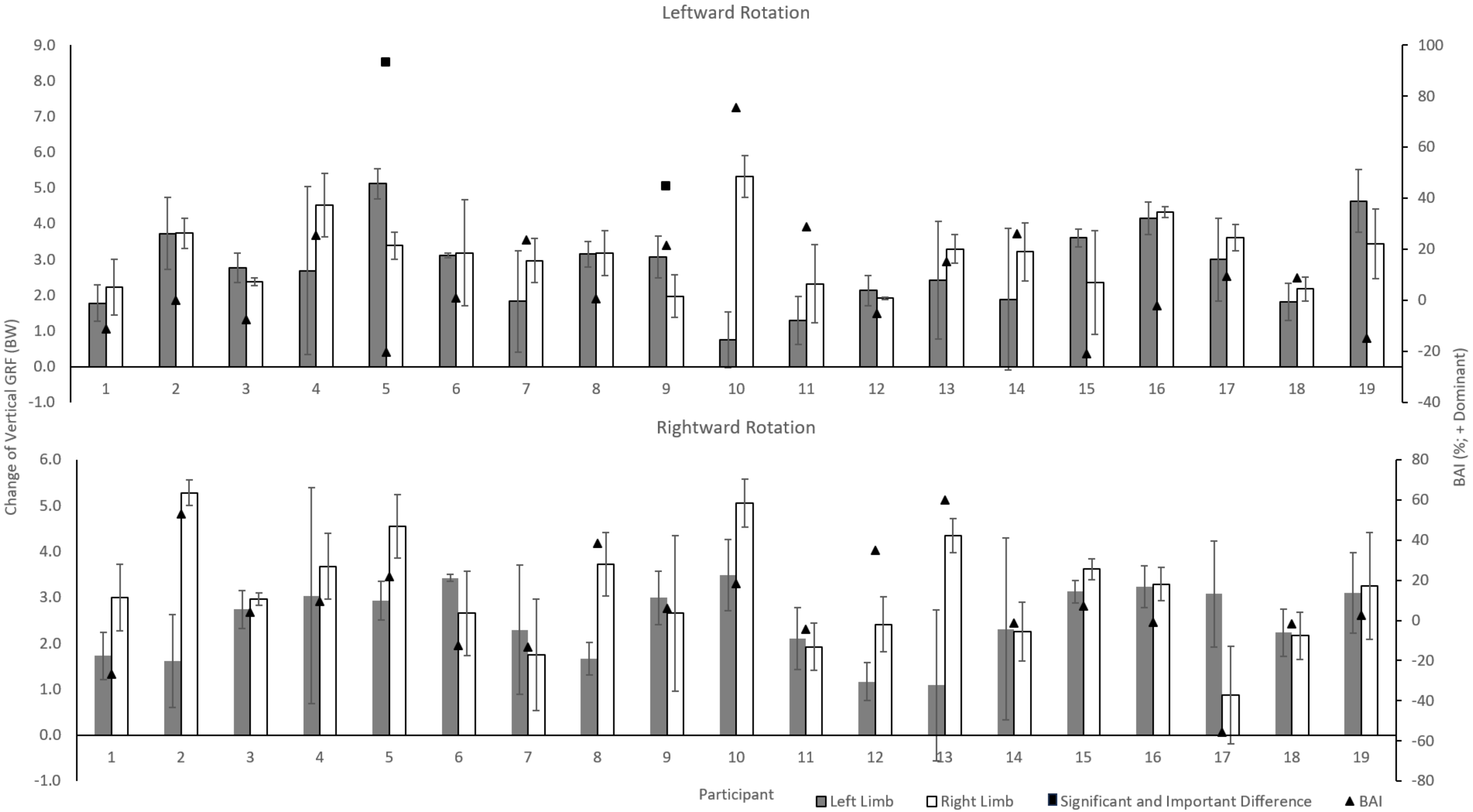
Figure 6. Limb-Specific Changes in Vertical Ground Reaction Force and the Corresponding Bilateral Asymmetry Indices for Each Participant During the Control Phase of Landings with Leftward and Rightward Rotation.

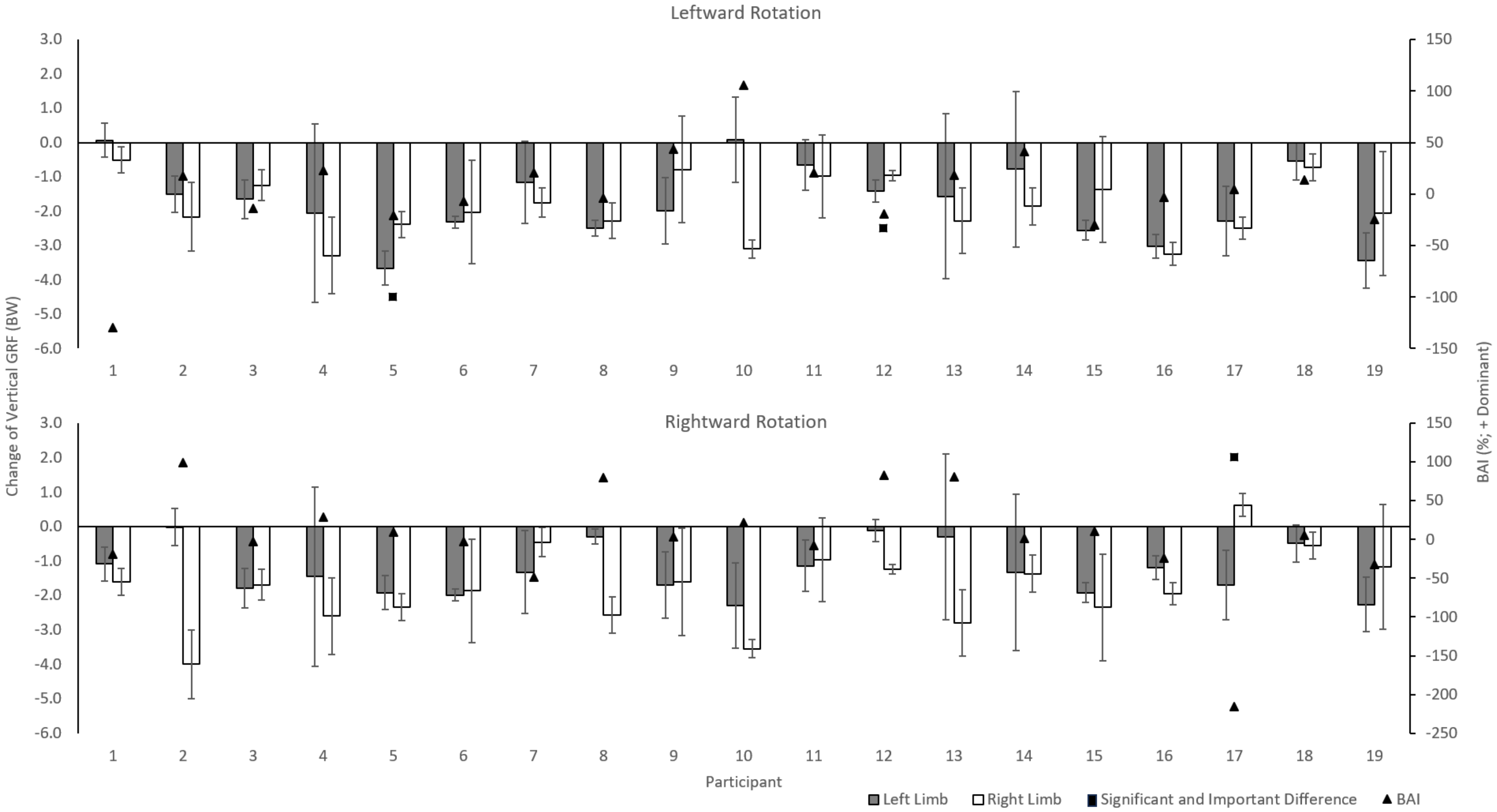
Notes – GRF: ground reaction force; BAI: Bilateral Asymmetry Index.

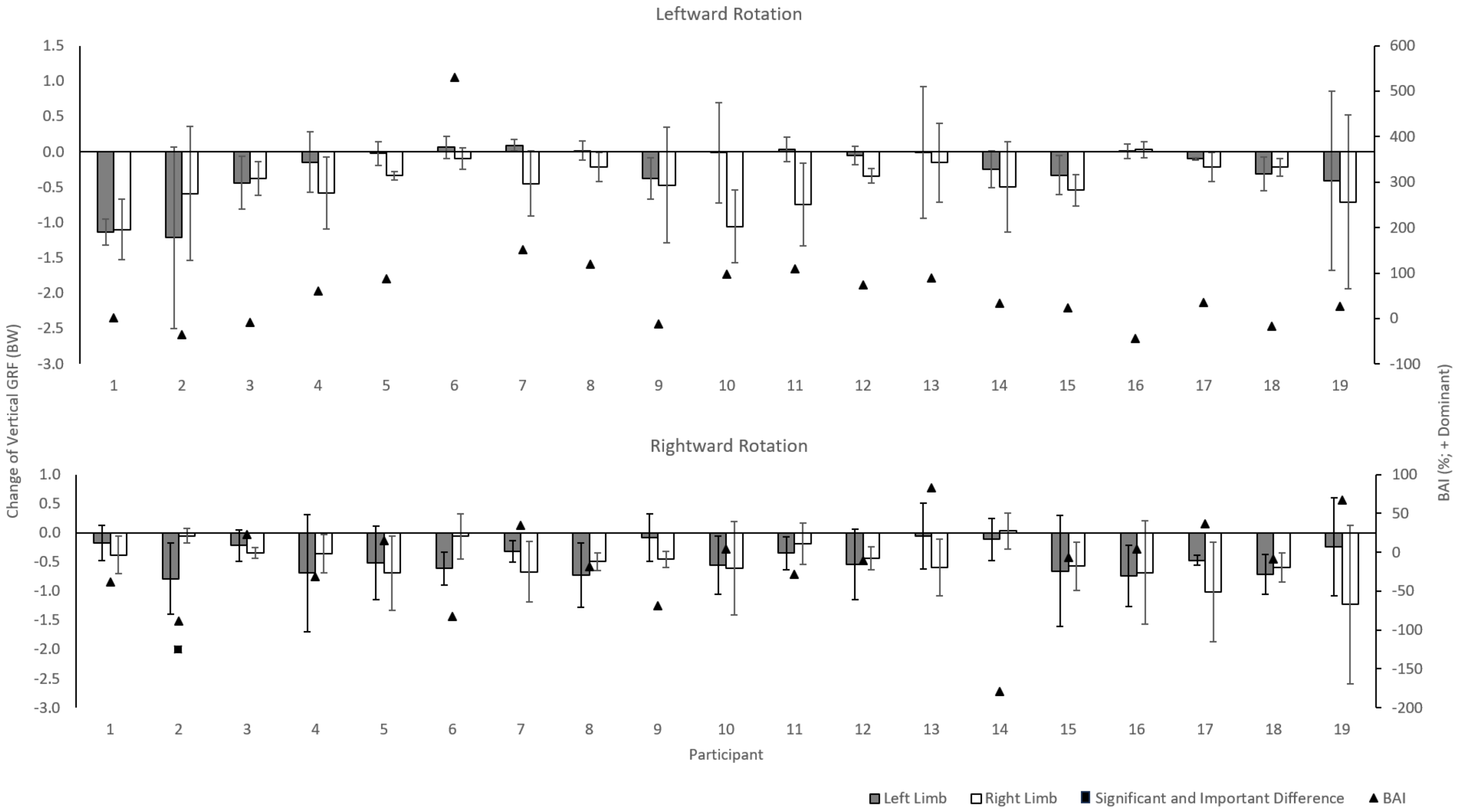

LOADING
ATTENUATION
CONTROL
Force (N)
3000
2500
2000
1500
1000
500
0
Velocity (m/s)
0.5
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
-3.0
Time (s)
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.50
Vertical GRF (N)
Vertical Velocity (m/s)


Landing Performance Index
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Landing Height (m)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
Landing Time (s)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19
Participant
Leftward
Rightward
Significant and Important Difference


Loading Time (s)
0.00
0.02
0.04
0.06
0.08
0.10
0.12
Attenuation Time (s)
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.16
Control Time (s)
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
Participant
Leftward
Rightward
Significant and Important Difference


Leftward Rotation
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1.0
100
80
60
40
20
0
-20
-40
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
Rightward Rotation
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1.0
80
60
40
20
0
-20
-40
-60
-80
Change of Vertical GRF (BW)
BAI (%; + Dominant)
Participant
Left Limb
Right Limb
Significant and Important Difference
BAI


Leftward Rotation
Rightward Rotation
Change of Vertical GRF (BW)
BAI (%; + Dominant)
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
-4.0
-5.0
-6.0
150
100
50
0
-50
-100
-150
-200
-250
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
Participant
Left Limb
Right Limb
Significant and Important Difference
BAI


Leftward Rotation
Rightward Rotation
Change of Vertical GRF (BW)
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
-3.0
BAI (%; + Dominant)
600
500
400
300
200
100
0
-100
50
-50
-150
-200
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
Participant
Left Limb
Right Limb
Significant and Important Difference
BAI