International Journal of Strength and Conditioning

Barker, L. A., Harry, J. R. (2022). Bilateral Ground Reaction Force Asymmetry During Supramaximal Drop Landings
International Journal of Strength and Conditioning
https://doi.org/10.47206/ijsc.v2i1.160

Bilateral Ground Reaction Force Asymmetry During Supramaximal Drop Landings

Leland A. Barker[1], John R. Harry[2]

[1]Department of Exercise Science & Pre-Health Professions, Creighton University, Omaha, NE, [2]Department of Kinesiology and Sport Management, Texas Tech University, Lubbock, TX

ABSTRACT

Bilateral vertical ground reaction forces (vGRF) asymmetries have not been investigated during supramaximal drop heights. The first purpose of this study was to investigate the influence of drop height on impact and attenuation vGRF impulses. 19 young adults completed the protocol (14 males, 5 females, age: 21.3 ± 0.75 years, mass: 75.1 ± 10.2 kg, height: 171.4 ± 7.9 cm, 1RM back squat relative to mass: 1.72 ± 0.4), which included bilateral drop landings starting at 0.3 m going up to 1.52 m in increments of 0.152 m. Asymmetries were calculated from impact impulse, loading rate, peak vGRF, attenuation impulse, and total impulse. Linear regressions analyzed these variables with respect to drop height at the group and individual levels. All dependent variables measuring asymmetrical force production produced negative regression slopes at the group level, but the adjusted R^2 values ranging 0.06 to 0.15 indicate drop height accounted for minimal variance in asymmetry variables. However, examination of individual asymmetry responses reveals noteworthy adjusted R^2 values for athlete monitoring and return to play considerations in competitive sport. Seven participants displayed significant reductions in asymmetry values as drop height increased with R^2 values ranging from 0.23-0.64. Practitioners and coaches using landing asymmetry measurements to support return to play decisions should consider the inclusion of larger drop heights to avoid false positive asymmetry results and encourage participants to land as quickly as possible with maximal effort.

Keywords: Asymmetry, Landing, Ground Reaction Forces

INTRODUCTION

Landings have been used to assess deceleration ability and motor control strategy (L. Barker et al., 2022) and bilateral asymmetry (Pedley et al., 2020) to evaluate performance and potential injury risk by examining discrete and continuous time points within the task. Landings are also used to study accommodation strategy, fatigue, and injury risk irrespective of asymmetry (Dufek et al., 1995; Dufek & Bates, 1990; James et al., 2003; Nordin et al., 2017; Zhang et al., 2000). Landing can be separated into impact and attenuation phases for in-depth assessments within key periods of the task (Harry et al., 2017). The impact phase occurs from initial contact to the peak vertical ground reaction force (vGRF) (Harry et al., 2017). The attenuation phase occurs from peak vGRF to the time when center of mass (COM) vertical velocity reaches zero (Harry et al., 2017). When landing from maximal effort vertical jumps, the rate of vGRF attenuation was reported to be significantly greater in healthy adults who land fast compared to slow, while the peak vGRF and rate of force development during impact did not differ (Harry et al., 2018). Dichotomous stances on landing mechanics exist among practitioners. This is because fast and stiff deceleration is important for time-sensitive performance (L. A. Barker et al., 2018; Kipp et al., 2018), but may introduce unnecessary injury risk if the landing forces are high and present knee abduction, femoral internal rotation, and foot pronation (Hewett et al., 2016). During the impact phase, hip joint contributions as a percentage of total eccentric work in the lower extremity joints were greater in slow landers (16.5% vs 8.1%, es: 1.10) while eccentric ankle joint contributions were greater in fast landers (46.4% vs 35.1%, es: 0.98). (Harry et al., 2018). During the attenuation phase, hip joint contributions were greater in slow landers (16.9% vs 31.3%, es: 1.07) while knee joint contributions were greater in fast landers (77.2% vs 64.2%, es: 0.99) (Harry et al., 2018). Thus, landing fast has been associated with greater eccentric work from the ankle joint during impact and the knee joint during attenuation (Harry et al., 2018). However, the impact and attenuation phases have not been investigated during supramaximal landing tasks, which we will operationally define as a drop height greater than the maximal jump height. Supramaximal landing tasks could be effective during preparation and training for improving deceleration ability to benefit populations in sport, tactical training and operations, and acrobatics.

In addition to impact and attenuation landing mechanics, bilateral asymmetry during landing may indicate small to moderate injury risk (Pedley et al., 2020). In addition, bilateral asymmetry may be particularly useful in guidance of return to play protocols (Paterno et al., 2011). Dynamic asymmetry is assessed with a variety of strategies, including unilateral and bilateral movements (i.e. dynamic force tests), isolated muscle tests (i.e. agonists and antagonists), and movement competency tests like the functional movement screen, Y balance test, and star excursion balance test (Helme et al., 2021). Recent research has reported significant variability in asymmetry measured from gross motor tasks (Bishop et al., 2021, 2022; Maloney et al., 2018; Newton et al., 2006), which included single leg hops, change of direction, and countermovement jump tests. During bilateral landing tasks, asymmetrical vGRF could be observed due to limb-specific neuromuscular control, musculoskeletal force output, or both. Deceleration demand of a bilateral submaximal landing task may be accomplished with a range of asymmetries from perfect symmetry (50% contribution from each leg) or near perfect asymmetry (i.e. 99% contribution from one leg, theoretically). In contrast, maximal effort landing tasks may reduce the number of available neuromuscular control options in response to greater mechanical demands. Differences in asymmetry between submaximal and maximal bilateral landing tasks may be used to identify neuromuscular control or musculoskeletal force output as the primary cause of asymmetry. For example, if a maximal effort produces minimal asymmetry and a submaximal effort produces large asymmetries, neuromuscular control may be the cause of those asymmetries. However, bilateral vGRF asymmetries have not been investigated during supramaximal drop heights.

The first purpose of this study was to investigate the influence of drop height on impact and attenuation vGRF impulses. We hypothesized increases in both impact and attenuation impulses as drop height increases in addition to a consistent ratio between impact and attenuation impulses. The second purpose of this study was to investigate bilateral vGRF asymmetries during impact and attenuation phases with increases in drop height. We hypothesized a reduction in asymmetries would occur with increasing drop heights due to the maximal effort required to land from supramaximal box heights.

MATERIALS AND METHODS

Experimental Approach

The current study is a new analysis of pre-existing data collected from a recently published study (L. Barker et al., 2022). Participants performed drop landings from increasing box heights up to 1.52 m (5 ft) in 0.15 m (6 in) increments to acquire vGRF data from supramaximal drop heights. During landing, vGRF impulse was determined bilaterally from the impact and attenuation phases and used for analysis. Group and single-subject regression analysis of impact, attenuation, and asymmetry with respect to drop height were used to analyze the dependent variables.

Participants

Twenty young adults were recruited to participate in the study, of which 19 completed the protocol and were included in the analysis (14 males, 5 females, age: 21.3 ± 0.75 years, mass: 75.1 ± 10.2 kg, height: 171.4 ± 7.9 cm, 1RM back squat relative to mass: 1.72 ± 0.4). All participants were college students with multiple years' experience with weight training (4.4 ± 2.3 years). Participants provided informed written consent prior to any testing procedures in accordance with Creighton University's Institutional Review Board (protocol #2001509). Following consent, all participants performed a 1 repetition maximum (1RM) back squat to confirm their 1RM was at least 1.25 times bodyweight to meet study inclusion criteria. Participants with acute or chronic musculoskeletal injuries influencing their ability to perform a drop landing were excluded from the study. Participants were instructed to wear athletic shoes (i.e. no specialty shoes) for all tests. All testing procedures were supervised by a Certified Strength and Conditioning Specialist.

Procedures

On the first day of testing, participants performed a standardized warm up consisting of 2 sets of 10 bodyweight lunges, 10 bodyweight squats, and 5 jumps at a self-selected pace. Following the warmup, participants began the 1RM back squat test, which consisted of 2 sets of 3-6 repetitions followed by sets of 1-3 repetitions with self-selected, increasing weights, until a 1RM was reached (Baechle et al., 2008). Each set was separated by at least 2 minutes. Participants also performed jumping tests on day 1 not included in the current study analysis. A minimum of 48 hours and maximum of a week rest was enforced before the second testing session.

On the second day of testing, participants repeated the standardized warmup and were given an opportunity to practice the drop landing test. All landing trials were performed on an in-ground dual force platform setup (Model 4060-07, Bertec, Columbus, Ohio) collecting GRF signals at 1000 Hz. Participants were asked to step off each box as consistently as possible and cued to "land as quickly as possible and hold their final position". Hands were free to move during landing but had to remain still at the end of the trial for a stable bodyweight measurement. The final position varied between standing upright and the minimum depth, but the minimum depth was considered the endpoint for trial calculations. Starting with a 0.30 m box (12 in), participants performed 4 trials from each box height, which increased by 0.152 m (6 inches) until a height of 1.52 m (5 ft) was reached for a total of 36 drop landing trials. Participants were allowed to rest ad libitum, which resulted in approximately 30-60 seconds between trials. Across the entire study pool, a total of 11 trials from 6 different participants were discarded as mistrials due to participant failure to remain still at the end of the trial, which produced miscalculations of vGRF attenuation impulses. All other trials were included in the analysis.

Data Analysis

All data analysis was performed using custom MATLAB scripts (MATLAB 2019a, MathWorks, Natick, MA). For all drop landing trials, raw GRF signals were first filtered with a 4th order Butterworth filter using a low pass cutoff frequency of 50 Hz and the vGRF were then summed from each force plate. The summed vGRF data array was flipped, which resulted in the vGRF signal resembling a squat jump and the ability to integrate the force signal to calculate points of interest. Using this flipped vertical GRF signal, bodyweight was calculated as the average vertical GRF of the first 0.5 seconds (i.e., when participants were motionless in their final landing position) (6). Data files were checked during collection to ensure participants were motionless for at least 0.5 seconds following landing. Vertical acceleration was calculated from the summed vGRF using Newton's 2nd Law ($\Sigma F = ma$), and then double time-integrated with the cumulative trapezoidal method to obtain vertical velocity and displacement of the center of mass. Initial landing impact was determined with a threshold of 20 N (determined according to the typical vGRF magnitude when these force plates are unloaded), and the end of the landing phase occurred when velocity reached 0, representing the time when downward motion was completed (Harry et al., 2018). vGRF impulse was calculated as the area under the vGRF-time curve, applied to the entire signal, the impact phase, and attenuation phase from the total vGRF signal. For asymmetry calculations, impulse was calculated from the left and right leg vGRF signals within the impact and attenuation timepoints. The impulse-momentum relationship was used to calculate impact velocity (net landing impulse (vGRF – force of gravity) divided by body mass), which was used to calculate drop height with the following equation of constant acceleration:

$$Drop\ height = \frac{Impact\ Velocity^2}{2g}$$

Peak vGRF and loading rate (peak vGRF divided by the time to peak vGRF) were determined from individual limbs for asymmetry analysis. All asymmetry values were calculated as a ratio of the left and right limbs (e.g. value of 1.0 represents perfect symmetry). However, this study is not concerned with the directionality of asymmetry, so 1 was subtracted from the asymmetry value and then an absolute value was determined. This process produced a value of 0 for perfect symmetry and positive values for asymmetries without regard for directionality toward left or right legs. Directionality was removed from asymmetry calculations because it could confound results. If directionality were included, one trial with asymmetry toward the right limb could be nullified by another trial with asymmetry toward the left limb during the regression analyses. The asymmetry ratio was calculated for the following dependent variables: peak vGRF, loading rate, impact phase impulse, attenuation phase impulse, and total impulse.

Statistical Analysis

Linear regression models were applied to all dependent variables with respect to drop height at both the group and individual levels. The standard error and p-values are provided for the slope and intercept coefficients. The adjusted R^2 value is provided in addition to the residual as a measure of model fit. Statistical significance was set a priori with an alpha level of 0.05.

RESULTS

Group results are presented in Table 1 in addition to scatter plots in Figure 1. The regression analysis for impact impulse with respect to drop height produced the greatest adjusted R^2 value of 0.44. All dependent variables measuring asymmetrical force production produced negative regression slopes at the group level, but the adjusted R^2 values ranging 0.06 to 0.15 indicate drop height accounted for minimal variance in asymmetry variables. However, examination of individual asymmetry responses reveals noteworthy adjusted R^2 values for athlete monitoring and return to play considerations in competitive sport. The slope coefficients from individual responses are displayed in Figure 2, where negative asymmetry values represent decreases in asymmetry variables as drop height increases. Statistical significance and adjusted R^2 values for individual linear regressions are presented in Figures 2-4. For reference, the average CMJ height across the participant pool was 0.35 ± 0.07 m, making the highest box (1.52 m) 4.34 times higher than CMJ height.

Table 1. Group Linear Regression Results. Slopes and intercepts are provided with standard errors for each variable with respect to increases in drop height. The adjusted R^2 and residuals are reported as measures of variance and regression fit. * denotes statistical significance at $p < 0.05$.

Variable	Slope ± Standard Error	Intercept ± Standard Error	Adjusted R^2	Residual
Peak Fz Asymmetry	-0.12 ± 0.018*	0.28 ± 0.014*	0.06	0.12
Loading Rate Asymmetry	-0.31 ± 0.043*	0.57 ± 0.035*	0.07	0.23
Impulse Asymmetry	-0.17 ± 0.016*	0.27 ± 0.013*	0.15	0.09
Impact Impulse Asymmetry	-0.20 ± 0.022*	0.30 ± 0.018*	0.11	0.09
Attenuation Impulse Asymmetry	-0.17 ± 0.017*	0.28 ± 0.014*	0.13	0.10
Impact Impulse	49.32 ± 2.17*	55.12 ± 1.77*	0.44	15.00
Attenuation Impulse	211.51 ± 9.11*	250.95 ± 7.43*	0.45	62.98
Impact/Attenuation Impulse Ratio	-0.006 ± 0.006	0.19 ± 0.005*	0.0001	0.03

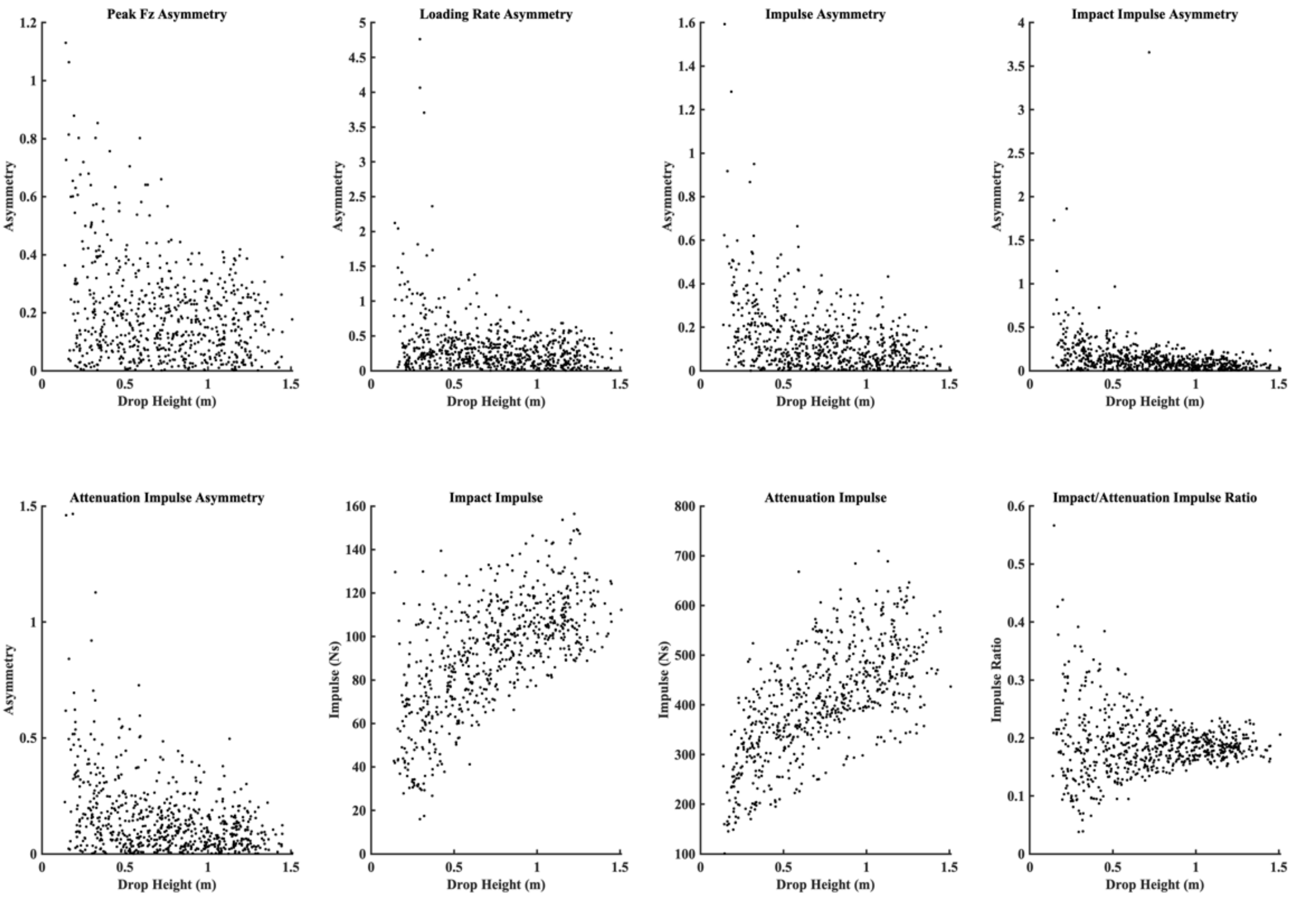

Figure 1. Complete group trial data for each dependent variable with respect to drop height.

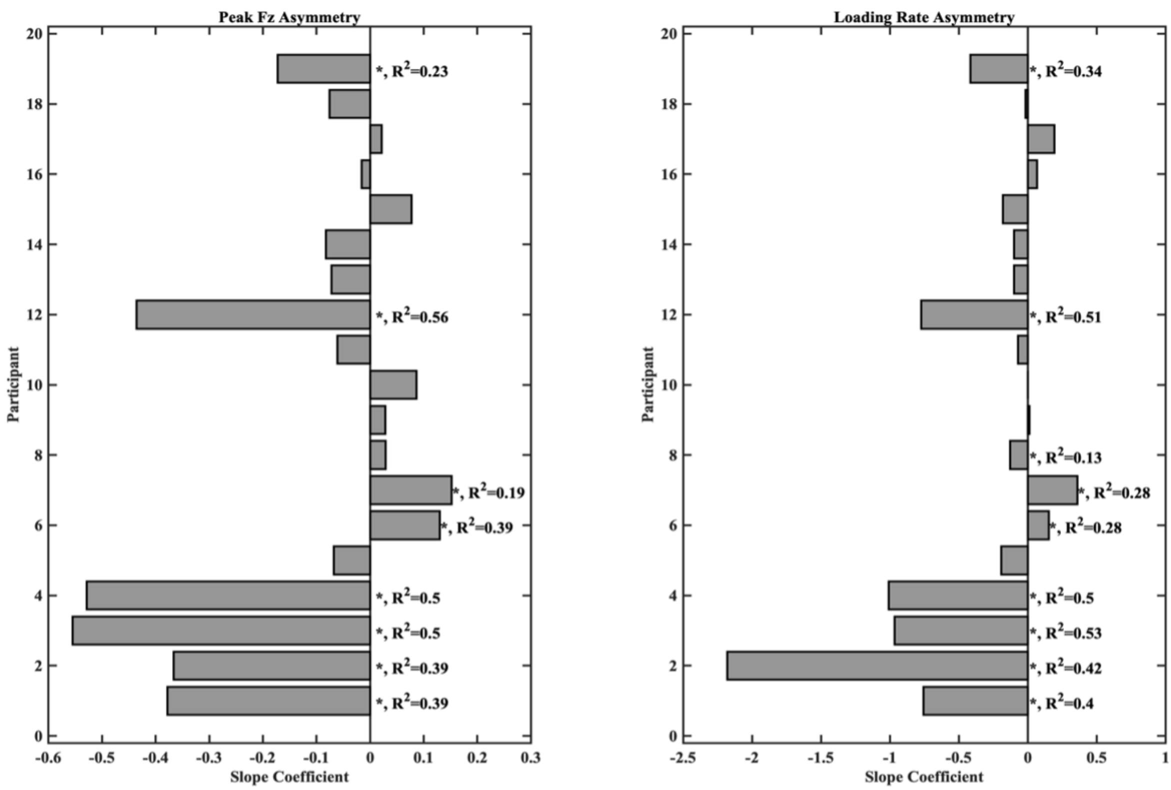

Figure 2. Individual participant responses for peak Fz and loading rate asymmetries. The slope coefficient of the individual linear regression lines is accompanied by adjusted R2 values if statistically significant. A negative slope indicates a reduction in asymmetry as drop height increased. * denotes statistical significance at $p < 0.05$.

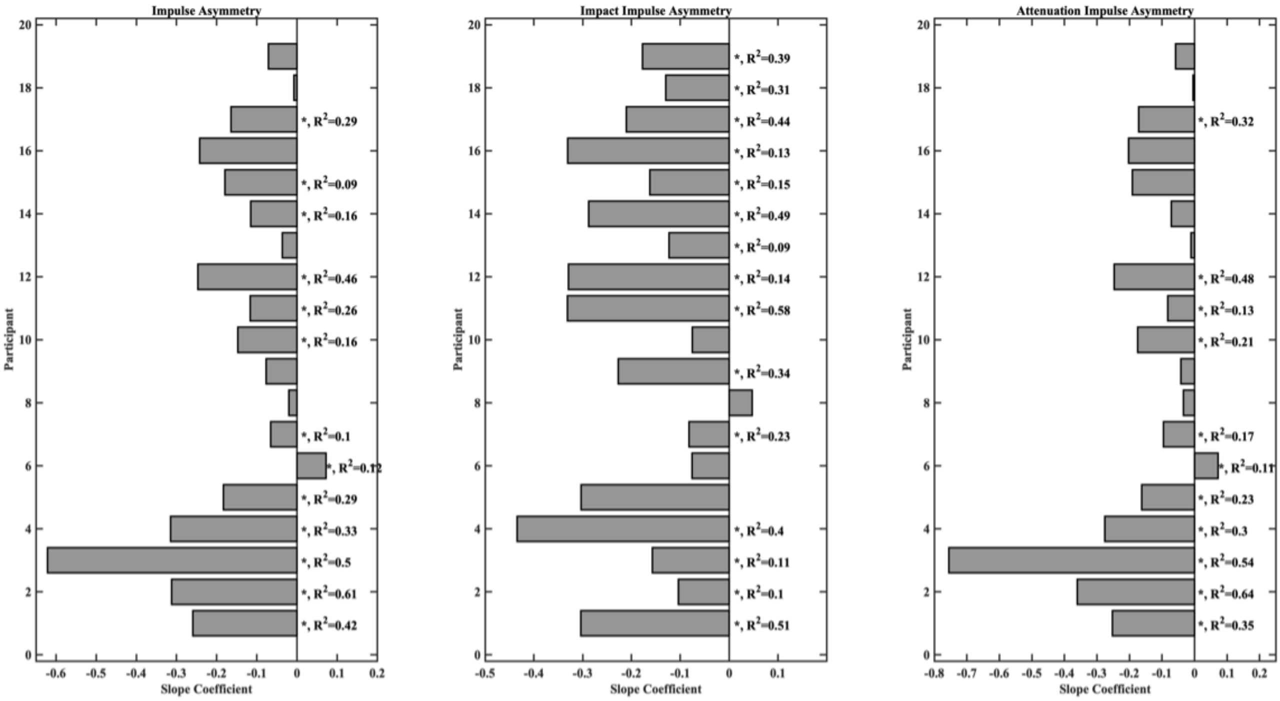

Figure 3. Individual participant responses for total impulse, impact impulse, and attenuation impulse asymmetries. The slope coefficient of the individual linear regression lines is accompanied by adjusted R^2 values if statistically significant. A negative slope indicates a reduction in asymmetry as drop height increased. * denotes statistical significance at $p < 0.05$.

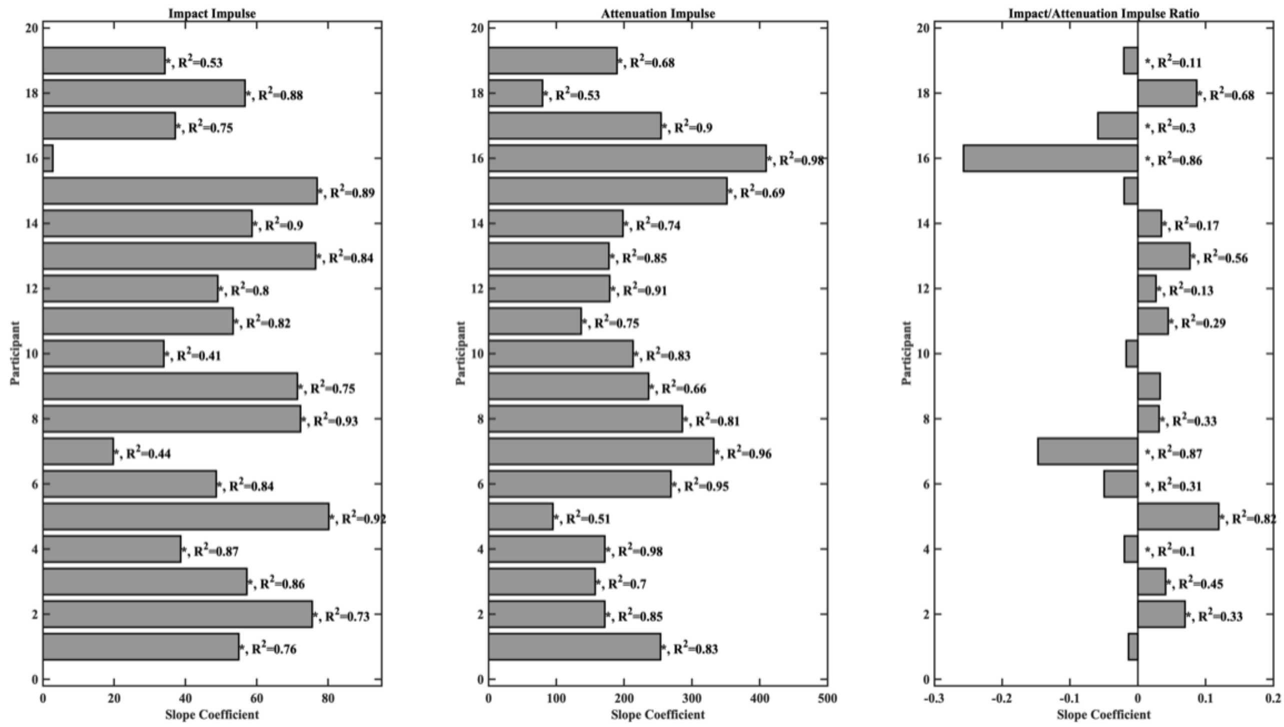

Figure 4. Individual participant responses for bilateral impact impulse, attenuation impulse, and the impact to attenuation impulse ratio. The slope coefficient of the individual linear regression lines is accompanied by adjusted R^2 values if statistically significant. * denotes statistical significance at $p < 0.05$.

DISCUSSION

The current study tested bilateral drop landings and observed negative slope coefficients and weak adjusted R^2 values across all vGRF asymmetry variables with respect to drop height. These results indicate a weak influence of drop height on bilateral vGRF asymmetry across the group, but some individual responses presented significant reductions in asymmetry when landing from increased heights. For example, the slope coefficient's adjusted R^2 value was 0.14 for the group impulse asymmetry, but there were seven participants with adjusted R^2 values ranging between 0.26-0.61. Asymmetry during the impact and attenuation phases followed a similar pattern. The slope coefficient's adjusted R^2 at the group level was 0.11 and 0.13 for the impact and attenuation impulse asymmetry, respectively, while nine participants produced adjusted R^2 values ranging between 0.23-0.58 for impact impulse asymmetry, and seven participants produced adjusted R^2 values ranging between 0.23-0.64 for attenuation impulse asymmetry. Generalizing our results to competitive athletes should be cautioned because these participants are healthy recreationally active adults, but the individual responses are important to consider for athlete monitoring and return to play protocols. Our results suggest the neuromuscular system can produce more asymmetry during submaximal landing tasks, perhaps because more neuromuscular control solutions are available to employ and accommodate submaximal landing demands. For example, the impulse required to complete a submaximal landing task could be accomplished with a range of activations from either limb, but a maximal landing task requires both limbs to activate maximally. Therefore, bilateral landing tasks assessing force production asymmetries may require greater intensities to reduce variability due to activation strategies and avoid false positive asymmetry results. The same notion may not be necessary for jump testing where maximal effort is assumed. Alternatively, supramaximal landing training may lead to greater deceleration capacity and increases in asymmetry variability during submaximal drop landings. An increase in asymmetry variability from structured training may represent an increase in motor strategy options and performance akin to the evidence of an optimal state of variability for healthy and skillful movement (Stergiou & Decker, 2011).

To promote maximal effort during landing tasks, it is important to individualize box heights due to the well-documented inter-individual variations during identical physical activities (Bates et al., 2016; Harry et al., 2020). Consider the following example: an athlete produces large asymmetries when performing a drop landing from a 0.3-meter box height but produces perfect symmetry as the box height increases above 1 meter. The asymmetry observed from the lower box height may be due to neuromuscular control compared to the higher box height that requires maximal effort and restricts neuromuscular activation options. If the higher box height is not tested, practitioners may trigger a plan to rebalance the athlete or continue rehabilitation, which may not be warranted. Thus, greater landing intensities could reduce the influence of neuromuscular control variations on asymmetrical force outputs to improve reliability and utility of asymmetry tests to predict injury and determine readiness to return to sport following injury.

The impact and attenuation phases responded in accordance with our hypothesis. The impact to attenuation ratios did not change with increases in box height. We report a slope coefficient of -0.001 ± 0.006 ($p > 0.05$) and an intercept value of 0.19 ± 0.005 ($p < 0.05$) with adjusted R2 of 0.0001 at the group level, indicating the impact impulse holds steady at approximately 19% of the attenuation impulse as drop heights increase towards 1.5 meters. For strength coaches and physical therapists drop landings can be implemented with higher heights with confidence the eccentric demand will increase proportionally across impact and attenuation phases. Naturally, practitioners may be hesitant to implement high intensity landing exercises because of a perceived injury risk, but the current study protocol required recreationally active participants to be able to back squat 125% of bodyweight and resulted in no injury occurrences. Further, there are a few studies challenging the volume (Dufek & Bates, 1990) and intensity (Hyoku, 1984; McNitt-Gray, 1993) of landings without any reported injuries. Therefore, landing from heights beyond 1m have been safely implemented in recreationally active and healthy athletes with requisite lower body strength. Most team sporting movements do not require landing from heights beyond maximal jump height, but they may require quick deceleration from high-speed sprints. Further, challenging landing tasks are common during many tactical and acrobatic movements. Supramaximal landing exercises within a structured and progressively overloaded program may be particularly well-suited to improving eccentric performance in athletes as a novel eccentric stimulus for sport preparation.

However, there are currently no known studies utilizing supramaximal landing tasks in a structured training program to improve eccentric performance. The most comparative training research to supramaximal landing training is the wealth of research on plyometrics and drop jump training, but these studies focus on improvements in jumping performance (i.e. jump height, reactive strength index, etc.) rather than eccentric neuromuscular performance (Bobbert, 1990; Ramirez-Campillo et al., 2018). Two drop jump training studies incorporated drops of 1 meter or greater (Bobbert, 1990; Clutch et al., 1983), but did not quantify eccentric performance. According to a recent systematic review, eccentric training programs typically administer supramaximal resistance training and single joint isokinetic exercises (Douglas et al., 2017). Injury prevention programs successful at improving landing biomechanics- reductions in frontal plane hip and knee moments, and dynamic trunk control- primarily use plyometrics, balance and proprioception, and strength training exercises (Hewett et al., 2016; Lopes et al., 2018). The lack of research investigating supramaximal landing exercises and training, therefore, could be a valuable and novel agenda for future research focused on eccentric performance and injury prevention.

CONCLUSION AND PRACTICAL APPLICATIONS

Bilateral asymmetries during landing presented variable individual responses to increases in drop height up to 1.5 meters. Practitioners and coaches using landing asymmetry measurements to support return to play decisions should consider the inclusion of larger drop heights to avoid false positive results and encourage maximal effort. While supramaximal drop heights present dichotomy between injury risk and eccentric performance, drop landings from supramaximal heights can elicit a potent eccentric stimulus. Future research is required to determine functional criteria for drop height intensities and if chronic supramaximal drop landings can stimulate novel adaptations to improve eccentric abilities of the lower extremity neuromusculoskeletal system.

ACKNOWLEDGEMENTS

We would like to thank the participants in the study as well as the undergraduate students who made this data collection possible.

REFERENCES

1. Baechle, T. R., Earle, R. W., & Association (U.S.), N. S. & C. (2008). Essentials of Strength Training and Conditioning. Human Kinetics. https://books.google.com/books?id=rk3SX8G5Qp0C
2. Barker, L. A., Harry, J. R., & Mercer, J. A. (2018). Relationships Between Countermovement Jump Ground Reaction Forces and Jump Height, Reactive Strength Index, and Jump Time. Journal of Strength and Conditioning Research, 32(1), 248–254. https://doi.org/10.1519/JSC.0000000000002160
3. Barker, L., Siedlik, J., Magrini, M., Uesato, S., Wang, H., Sjovold, A., Ewing, G., & Harry, J. R. (2022). Eccentric Force Velocity Profiling: Motor Control Strategy Considerations and Relationships to Strength and Jump Performance. Journal of Strength and Conditioning Research, Publish Ahead of Print. https://doi.org/10.1519/JSC.0000000000004309
4. Bates, B. T., Dufek, J. S., James, C. R., Harry, J. R., & Eggleston, J. D. (2016). The influence of experimental design on the detection of performance differences. Measurement in Physical Education and Exercise Science, 20(4), 200–207.
5. Bishop, C., Abbott, W., Brashill, C., Turner, A., Lake, J., & Read, P. (2022). Bilateral vs. Unilateral Countermovement Jumps: Comparing the Magnitude and Direction of Asymmetry in Elite Academy Soccer Players. Journal of Strength and Conditioning Research, 36(6), 1660–1666. https://doi.org/10.1519/JSC.0000000000003679
6. Bishop, C., Read, P., McCubbine, J., & Turner, A. (2021). Vertical and Horizontal Asymmetries Are Related to Slower Sprinting and Jump Performance in Elite Youth Female Soccer Players. Journal of Strength and Conditioning Research, 35(1), 56–63. https://doi.org/10.1519/JSC.0000000000002544
7. Bobbert, M. F. (1990). Drop jumping as a training method for jumping ability. Sports Medicine, 9(1), 7–22.
8. Clutch, D., Wilton, M., McGown, C., & Bryce, G. R. (1983). The Effect of Depth Jumps and Weight Training on Leg Strength and Vertical Jump. Research Quarterly for Exercise and Sport, 54(1), 5–10. https://doi.org/10.1080/02701367.1983.10605265
9. Douglas, J., Pearson, S., Ross, A., & McGuigan, M. (2017). Chronic Adaptations to Eccentric Training: A Systematic Review. Sports Medicine, 47(5), 917–941. https://doi.org/10.1007/s40279-016-0628-4
10. Dufek, J. S., & Bates, B. T. (1990). The evaluation and prediction of impact forces during landings: Medicine & Science in Sports & Exercise, 22(3), 370???377. https://doi.org/10.1249/00005768-199006000-00014
11. Dufek, J. S., Bates, B. T., Stergiou, N., & James, C. R. (1995). Interactive effects between group and single-subject response patterns. Human Movement Science, 14(3), 301–323. https://doi.org/10.1016/0167-9457(95)00013-I
12. Harry, J. R., Barker, L. A., Eggleston, J. D., & Dufek, J. S. (2018). Evaluating Performance During

Maximum Effort Vertical Jump Landings. Journal of Applied Biomechanics, 34(5), 403–409. https://doi.org/10.1123/jab.2017-0172
13. Harry, J. R., Eggleston, J. D., Dufek, J. S., & James, C. R. (2020). Single-subject analyses reveal altered performance and muscle activation during vertical jumping. Biomechanics, 1(1), 15–28.
14. Harry, J. R., Freedman Silvernail, J., Mercer, J. A., & Dufek, J. S. (2017). Comparison of pre-contact joint kinematics and vertical impulse between vertical jump landings and step-off landings from equal heights. Human Movement Science, 56, 88–97. https://doi.org/10.1016/j.humov.2017.10.022
15. Helme, M., Tee, J., Emmonds, S., & Low, C. (2021). Does lower-limb asymmetry increase injury risk in sport? A systematic review. Physical Therapy in Sport, 49, 204–213. https://doi.org/10.1016/j.ptsp.2021.03.001
16. Hewett, T. E., Myer, G. D., Ford, K. R., Paterno, M. V., & Quatman, C. E. (2016). Mechanisms, prediction, and prevention of ACL injuries: Cut risk with three sharpened and validated tools: ACL INJURY PREVENTION. Journal of Orthopaedic Research, 34(11), 1843–1855. https://doi.org/10.1002/jor.23414
17. Hyoku, C. (1984). A Effect of dropping height on a buffer action in landing. Proc Jpn Soc Biomech, 1984, 203–207.
18. James, C. R., Bates, B. T., & Dufek, J. S. (2003). Classification and Comparison of Biomechanical Response Strategies for Accommodating Landing Impact. Journal of Applied Biomechanics, 19(2), 106–118. https://doi.org/10.1123/jab.19.2.106
19. Kipp, K., Kiely, M. T., Giordanelli, M. D., Malloy, P. J., & Geiser, C. F. (2018). Biomechanical Determinants of the Reactive Strength Index During Drop Jumps. International Journal of Sports Physiology and Performance, 13(1), 44–49. https://doi.org/10.1123/ijspp.2017-0021
20. Lopes, T. J. A., Simic, M., Myer, G. D., Ford, K. R., Hewett, T. E., & Pappas, E. (2018). The Effects of Injury Prevention Programs on the Biomechanics of Landing Tasks: A Systematic Review With Meta-analysis. The American Journal of Sports Medicine, 46(6), 1492–1499. https://doi.org/10.1177/0363546517716930
21. Maloney, S. J., Richards, J., & Fletcher, I. M. (2018). A Comparison of Bilateral and Unilateral Drop Jumping Tasks in the Assessment of Vertical Stiffness. Journal of Applied Biomechanics, 34(3), 199–204. https://doi.org/10.1123/jab.2017-0094
22. McNitt-Gray, J. L. (1993). Kinetics of the lower extremities during drop landings from three heights. Journal of Biomechanics, 26(9), 1037–1046. https://doi.org/10.1016/S0021-9290(05)80003-X
23. Newton, R. U., Gerber, A., Nimphius, S., Shim, J. K., Doan, B. K., Robertson, M., Pearson, D. R., Craig, B. W., Häkkinen, K., & Kraemer, W. J. (2006). Determination of functional strength imbalance of the lower extremities. The Journal of Strength & Conditioning Research, 20(4), 971–977.
24. Nordin, A. D., Dufek, J. S., James, C. R., & Bates, B. T. (2017). Classifying performer strategies in drop landing activities. Journal of Sports Sciences, 35(18), 1858–1863. https://doi.org/10.1080/02640414.2016.1240876
25. Paterno, M. V., Schmitt, L. C., Ford, K. R., Rauh, M. J., Myer, G. D., & Hewett, T. E. (2011). Effects of Sex on Compensatory Landing Strategies Upon Return to Sport After Anterior Cruciate Ligament Reconstruction. Journal of Orthopaedic & Sports Physical Therapy, 41(8), 553–559. https://doi.org/10.2519/jospt.2011.3591
26. Pedley, J. S., Lloyd, R. S., Read, P. J., Moore, I. S., De Ste Croix, M., Myer, G. D., & Oliver, J. L. (2020). Utility of Kinetic and Kinematic Jumping and Landing Variables as Predictors of Injury Risk: A Systematic Review. Journal of Science in Sport and Exercise, 2(4), 287–304. https://doi.org/10.1007/s42978-020-00090-1
27. Ramirez-Campillo, R., Álvarez, C., García-Hermoso, A., Ramírez-Vélez, R., Gentil, P., Asadi, A., Chaabene, H., Moran, J., Meylan, C., García-de-Alcaraz, A., Sanchez-Sanchez, J., Nakamura, F. Y., Granacher, U., Kraemer, W., & Izquierdo, M. (2018). Methodological Characteristics and Future Directions for Plyometric Jump Training Research: A Scoping Review. Sports Medicine, 48(5), 1059–1081. https://doi.org/10.1007/s40279-018-0870-z
28. Stergiou, N., & Decker, L. M. (2011). Human movement variability, nonlinear dynamics, and pathology: Is there a connection? Human Movement Science, 30(5), 869–888. https://doi.org/10.1016/j.humov.2011.06.002
29. Zhang, S.-N., Bates, B. T., & Dufek, J. S. (2000). Contributions of lower extremity joints to energy dissipation during landings: Medicine & Science in Sports & Exercise, 32(4), 812–819. https://doi.org/10.1097/00005768-200004000-00014