International Journal of Strength and Conditioning

Barker, L., Marcuzzo, L., Wright, N., Hulse, T., Patterson, C., Dishno, O., & Harry, J. (2026). Differences in Deceleration Mechanics from Mass- vs Velocity-Dominant Impact Momentum. International Journal of Strength and Conditioning
https://doi.org/10.47206/ijsc.v6i1.387

Differences in Deceleration Mechanics from Mass- vs Velocity-Dominant Impact Momentum

Leland Barker[1]*, Leah Marcuzzo[1], Nick Wright[1], Trey Hulse[1], Carter Patterson[1], Olivia Dishno[1] and John Harry[2]

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

*Corresponding Author: Lelandbarker@creighton.edu

ABSTRACT

The purpose of this study was to determine how landing mechanics differ when impact momentum is manipulated by drop height (HEIGHT) compared to external loading (LOAD). 15 recreationally trained adults (10 males 5 females, 21.8 ± 3.5 years, 78.4 ± 13.2 kg, back squat 1RM: 127.6 ± 35.9 kg, back squat 1RM relative to mass: 1.61 ± 0.26) performed drop landings with bodyweight from 0.6 m, 0.91 m, and 1.22 m, in addition to externally loaded (via kettlebell) drop landings from 0.6 m with 16 kg, 28 kg, and 40 kg. Vertical ground reaction forces were analyzed for average force and velocity, landing depth, loading impulse, and attenuation impulse. Regression analysis was performed on each variable with respect to impact momentum with an alpha level of 0.01 (Bonferroni correction). The strongest relationships, identified by regressions with an R^2 greater than 0.5, were attenuation impulse for both HEIGHT (R^2= 0.839) and LOAD (R^2= 0.656), and average vGRF with LOAD (R^2= 0.617). Moderate relationships, identified by regressions with an R^2 between 0.3 and 0.5, were loading impulse with HEIGHT (R^2= 0.322), landing depth with HEIGHT (R^2= 0.412), and average vGRF with HEIGHT (R^2= 0.441). Weak relationships, identified by regressions with an R^2 less than 0.3, were loading impulse with LOAD (R^2= 0.030), landing depth with LOAD (R^2= 0.149), and average velocity with HEIGHT (R^2= 0.161). Loading impulse with LOAD and average velocity with LOAD were the only regressions to not be statistically significant, indicating the regression equation did not predict loading impulse better than the average across all trials. Administering the drop landing intensity with HEIGHT and LOAD led to some contrasting responses from the neuromusculoskeletal system, and future research is warranted to determine acute responses and eventual training effects, especially regarding individual joint kinetics.

INTRODUCTION

Deceleration performance is coveted in sports involving frequent, maximal effort changes of direction and stopping tasks. Poor deceleration ability during competition may result in lack of separation from a defender (Dos'Santos et al., 2022; Young et al., 2022), slower times to takeoff when jumping (Barker et al., 2018), and increased risk of injury (Hewett et al., 2016; McBurnie et al., 2022). Further, fatigue may reduce acceleration capacity (Harper et al., 2019; Komi, 2000; Russell et al., 2016) and lead to athletes' displaying compromised braking and stretch-shortening cycle performances. Thus, coaches and practitioners might prioritize training strategies to improve athletes' neuromusculoskeletal function during deceleration tasks. Training methodologies for this purpose are eccentrically focused, taking advantage of strength, power, plyometric, and sport specific changes of direction training exercises (Cormie et al., 2010; Douglas et al., 2017; Kijowksi et al., 2015; Wirth et al., 2015).

The drop landing (when a participant steps off a box and lands) is one example of an exercise isolating the eccentric action of the lower extremity

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for both research testing and training. Compared to isokinetic eccentric testing, dynamic landing tasks are more applicable to sporting movements, but introduces significant variability in force and velocity relationships due to the athlete's selection of specific motor control landing strategies (Barker et al., 2022). For example, the landing depth is free to vary and influence eccentric power output, such as high forces, fast landing times, and small landing depths versus lower forces, slower landing times, and large landing depths (Barker et al., 2022). The drop landing, in addition to the drop jump (when a jump immediately follows landing), is typically used to screen technique for overuse injury risk, rehabilitation progression, and performance by analyzing lower extremity alignment, loading and attenuation forces, or both (Ambegaonkar et al., 2011; Hewett et al., 2005, 2016; Horita et al., 1999; Lopes et al., 2018; McNitt-Gray, 1993; Paterno et al., 2011). However, there is additional utility of the drop landing for training purposes because of its potential for progressive overload and creating eccentric demands beyond a athlete's maximal jump height (Barker et al., 2022), thereby providing a supramaximal loading stimulus.

Supramaximal loading during the drop landing could be administered by an increase in drop height beyond maximal jump height, external loading added to the performer, or a combination thereof. With impact momentum- the momentum at initial contact- a supramaximal stimulus requires greater momentum than would occur when landing from peak jump height without added mass. Thus, manipulating height and external load may provide a tool to administer training variation and overload when targeting certain "velocity-specific" eccentric loads. However, a short drop height cannot provide a supramaximal demand without large external loads. A velocity-specific approach of this kind has potential to optimize eccentric training through manipulations of drop height and loading, which calls for investigation into the force-velocity relationships and the loading and attenuation phases of deceleration during landing.

The loading phase of landing starts at initial touchdown and ends at the first vertical ground reaction force (vGRF) peak, while the attenuation phase start at the first vGRF peak and ends once the center of mass reaches zero velocity, respectively (Barker & Harry, 2022; Harry et al., 2018). High forces during the loading phase coinciding with poor lower extremity alignment present risk of injury to the musculoskeletal system (Hewett et al., 2016), but high loading forces may be necessary during time-sensitive tasks in competitive sport (Barker et al., 2022; Barker et al., 2018). The dichotomy of this motor decision or strategy may be why supramaximal drop landings are not commonly utilized to stimulate eccentric stress and adaptation- practitioners and researchers are primarily focused on avoiding the acute risk of injury during landing tasks. However, previous research has demonstrated recreational athletes to be capable of safely performing supramaximal landing tasks (Barker et al., 2022; Dufek & Bates, 1990). Considering the principles of progressive overload, supramaximal landing training may stimulate chronic neuromusculoskeletal adaptation to promote both durability and performance during maximal deceleration tasks.

Fundamental landing mechanics have not been concurrently investigated regarding manipulations of drop height or external load during supramaximal drop landings. Therefore, the purpose of this study was to determine how landing mechanics (i.e. loading and attenuation forces, and force-velocity relationships) relate to impact momentum when manipulated by drop height (velocity) or external loading (mass). We hypothesized manipulations of external loading (with no changes in drop height) would lead to increases in attenuation forces and slower velocities while manipulations of drop height would lead to faster velocities and greater attenuation forces. A second hypothesis is manipulations in drop height will cause greater increases in loading phase forces compared to manipulations in external loading. The results of this study will inform practitioners about potentially specific demands of two methods of administering supramaximal landing tasks with the goal of improving our understanding of eccentric training exercises to promote durability and performance in athletes.

METHODS

Participants

A convenience sample of 15 healthy adults (10 males 5 females, 21.8 ± 3.5 years, 78.4 ± 13.2 kg, back squat 1RM: 127.6 ± 35.9 kg, back squat 1RM relative to mass: 1.61 ± 0.26) recruited from around the university and surrounding area volunteered for the study. The study protocol and recruitment procedures were approved by the University's Institutional Review Board (protocol

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#2003296). Each participant was familiarized to the landing tasks during the initial meeting following a 1-repetition maximum (1RM) back squat test, which included 3 warm up sets with increasing, self-selected loads followed by single repetitions until a 1RM was attained. Participants were not allowed to participate if they could not achieve a back squat 1RM of at least their own body mass, nor if they had any pre-existing or historical injuries restricting their ability to land and jump. All participants were currently resistance training at least 2 times per week at the time of participation.

Procedures

Participants performed a testing session including bilateral drop landings from 0.6 m, 0.91 m, and 1.22 m with no external load, and drop landings from 0.6 m while holding a kettlebell weighing 16 kg, 28 kg, and 40 kg (in the order provided). During pilot testing, a kettlebell was determined to be the easiest and safest method of loading because it can be held at the midline and allow the knees to function in a safe alignment. In contrast, a hex bar deadlift led to more valgus landing positions and the weight was more challenging to control and maneuver at the top of the box, and a weighted vest loading was limited in total weight capacity and led to unnecessary balance challenges. Participants performed 4 trials at each drop landing condition, instructed to land as quickly as possible in a safe position, which was always supervised by the research team. Participants were allowed to rest ad libitum, which was approximately 30 seconds between trials and 2 minutes between conditions. Longer breaks were suggested to participants if they had consecutive mistrials. Participants did not verbalize any concerns about fatigue during the study.

Ground reaction forces were sampled at 2000hz from bilateral force platforms (FP4060-07, Bertec Corporation, OH, USA) and exported to MATLAB (MATLAB 2022b, Mathworks, MA, USA) for analysis.

Data Analysis

This study was focused on the capacity to produce maximal force and stiffness during landing, so the trial with the minimum landing depth from each drop height was retained for analysis. All analyses were performed by a custom script (Matlab 2022b, Mathworks, Natick, MA). Dependent variables were average vGRF, average velocity, landing depth, loading impulse, and attenuation impulse. Average force and velocity were calculated from the time of impact, when the vGRF moves above 20N to account for empty force plate noise, to the time when vertical velocity crossed zero. Zero velocity was identified by integrating a reversed vGRF signal (Barker, 2022) with the trapezoidal method, which resembles a squat jump. Integration of the reversed vGRF signal is possible because participants must remain motionless after landing until the trial ends. The integration process enables the calculation of impact velocity, which is used to calculate impact momentum (impact velocity * system mass). Landing depth was also calculated from the integration process as the vertical displacement of the center of mass from initial impact to zero velocity when the COM reaches its lowest position. Finally, loading impulse was calculated from time of initial impact to the peak vGRF while attenuation impulse was calculated from the peak vGRF to zero velocity.

vGRF and impulses were not normalized to body mass for statistical analysis. All regressions are performed with respect to impact momentum-the product of system mass and impact velocity. Therefore, differences in participant mass are accounted for within the regression analysis and void the need to normalize forces to participant mass.

Statistical Analysis

Average vGRF, average velocity, landing depth, loading impulse, and attenuation impulse were all analyzed by linear regression with respect to impact momentum. This was done for both the landing conditions progressed by height (HEIGHT) and load (LOAD) for a total of 10 regressions. Standard error and R-squared values quantified the fit of each model. P-values are provided with an alpha level of 0.01 due to Bonferroni correction (0.05 / 5 dependent variables = 0.01), which identifies if the model predicts y-values significantly better than the average alone. Normality assumptions were tested with the Anderson-Darling test. Landing depth with respect to Impact Momentum applied by HEIGHT was the only dependent variable to fail normality assumptions.

RESULTS

Regression coefficients with standard errors, R-squared, *p*-value, and normality test values are provided in table 1. All regression models are presented in figures 1-5.

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Velocity presented negative slopes (faster velocities with increases in impact momentum) for HEIGHT (p<0.01, R^2 = 0.161) and LOAD (p>0.01, R^2 = 0.141) conditions, but the LOAD model was not statistically significant. The R^2 values of both conditions indicate significant within and between variability of the participant pool.

Landing depth also presented negative slopes (greater landing depths with increases in impact momentum) for both HEIGHT (slope = -8.9 x10^-4, p<0.01, R^2 = 0.412) and LOAD (slope = 5.0 x10^-4, p<0.01, R^2 = 0.149) condition, with the HEIGHT condition resulting in greater increases in landing depth per unit of impact momentum. The lower R^2 of the LOAD condition indicate more variability in landing depth compared to the HEIGHT condition.

Raw vGRF presented with a positive slope for both HEIGHT (slope = 3.42, p<0.01, R^2 = 0.441) and LOAD (slope = 5.45, p<0.01, R^2 = 0.617) conditions while LOAD resulted in greater increases in vGRF per unit of impact momentum. R^2 values indicate a moderate fit for HEIGHT and a strong fit for LOAD. The greatest average vGRF observed across the entire study occurred during the heaviest LOAD condition.

Loading impulse increased at a greater rate under the HEIGHT (Slope = 0.178, p<0.01, R^2 = 0.322) condition compared to the LOAD (Slope = 0.0676, p>0.01, R^2 = 0.030) condition, which was not statistically significant. The model for LOAD indicates loading impulse was highly variable and may not be influenced by increases in impact momentum within the current study's predictive range.

Attenuation impulse increased at a greater rate under the LOAD (Slope = 2.130, p<0.01, R^2 = 0.656) condition compared to the HEIGHT (Slope = 1.577, p<0.01, R^2 = 0.839) condition, both of which presented strong R^2 values and limited variability. The LOAD condition model elicited greater attenuation impulses across the predictive range.

DISCUSSION

The goal of this study was to investigate and describe the relationships of landing mechanics (average eccentric vGRF and velocity, landing depth, loading impulse, and attenuation impulse) to impact momentum during drop landings administered by increasing height or external load. The strongest relationships, identified by regressions with an R2 greater than 0.5, were attenuation impulse for both HEIGHT and LOAD, and average vGRF

Table 1. Linear regression models for all dependent variables with respect to impact momentum. The condition represents the method of implementing increases in supramaximal landing demand.

		Slope ± SE	Intercept ± SE	R^2	*p*-value	Normality	Normality test
Average vGRF	HEIGHT	3.42 ± 0.59	789.12 ± 186.37	0.441	0.00000	1	0.911
	LOAD	5.45 ± 0.66	220.30 ± 223.50	0.617	0.00000	1	0.556
Average Velocity	HEIGHT	-0.00128 ± 0.00044	-1.01 ± 0.14	0.161	0.00625	1	0.940
	LOAD	-0.00102 ± 0.00038	-0.86 ± 0.13	0.141	0.01092	1	0.056
Landing Depth	HEIGHT	-0.00089 ± 0.00016	-0.14 ± 0.05	0.412	0.00000	0	0.034
	LOAD	-0.00050 ± 0.00018	-0.24 ± 0.06	0.149	0.00870	1	0.147
Loading Impulse	HEIGHT	0.18 ± 0.04	28.25 ± 12.50	0.322	0.00005	1	0.165
	LOAD	0.07 ± 0.06	67.13 ± 20.02	0.030	0.25634	1	0.139
Attenuation Impulse	HEIGHT	1.58 ± 0.11	-30.30 ± 33.43	0.839	0.00000	1	0.930
	LOAD	2.13 ± 0.24	-108.99 ± 80.21	0.656	0.00000	1	0.299

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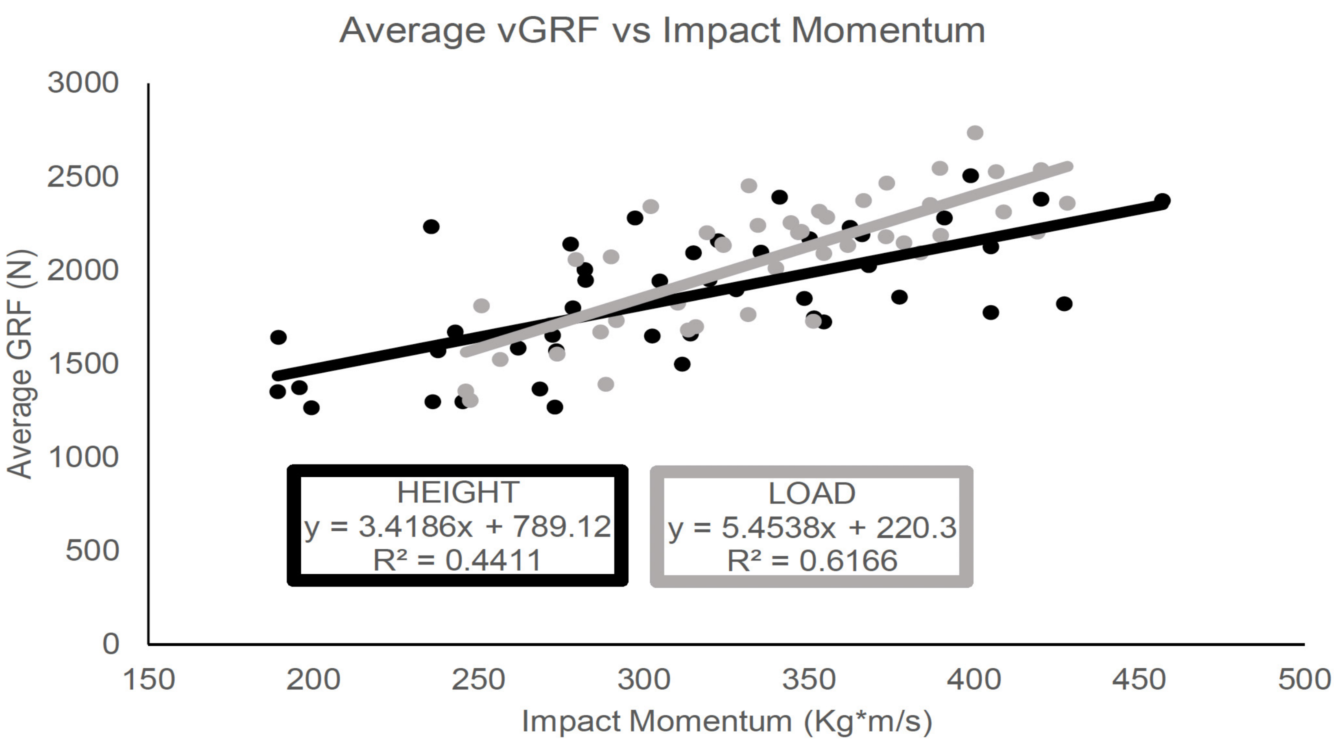

Figure 1. Average vGRF with respect to impact momentum for drop landings increased by HEIGHT (black) and LOAD (gray).

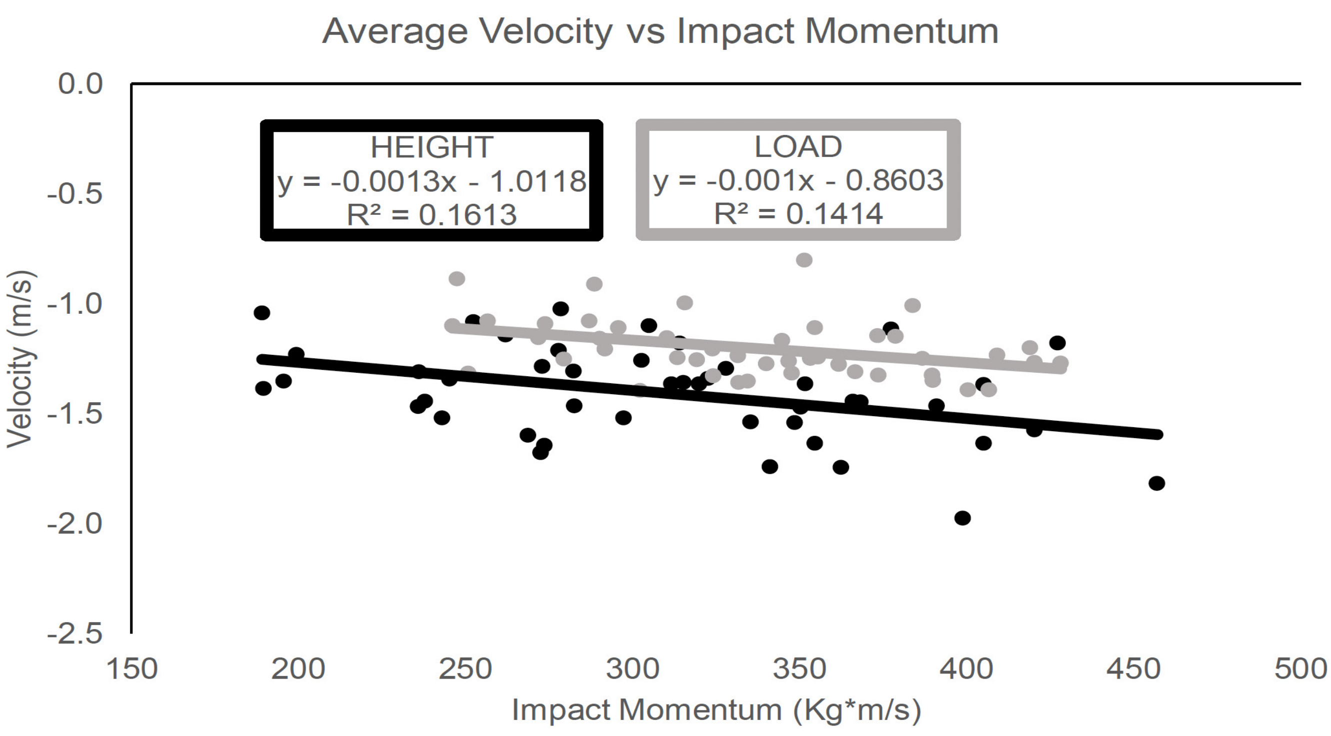

Figure 2. Average Velocity with respect to impact momentum for drop landings increased by HEIGHT (black) and LOAD (gray).

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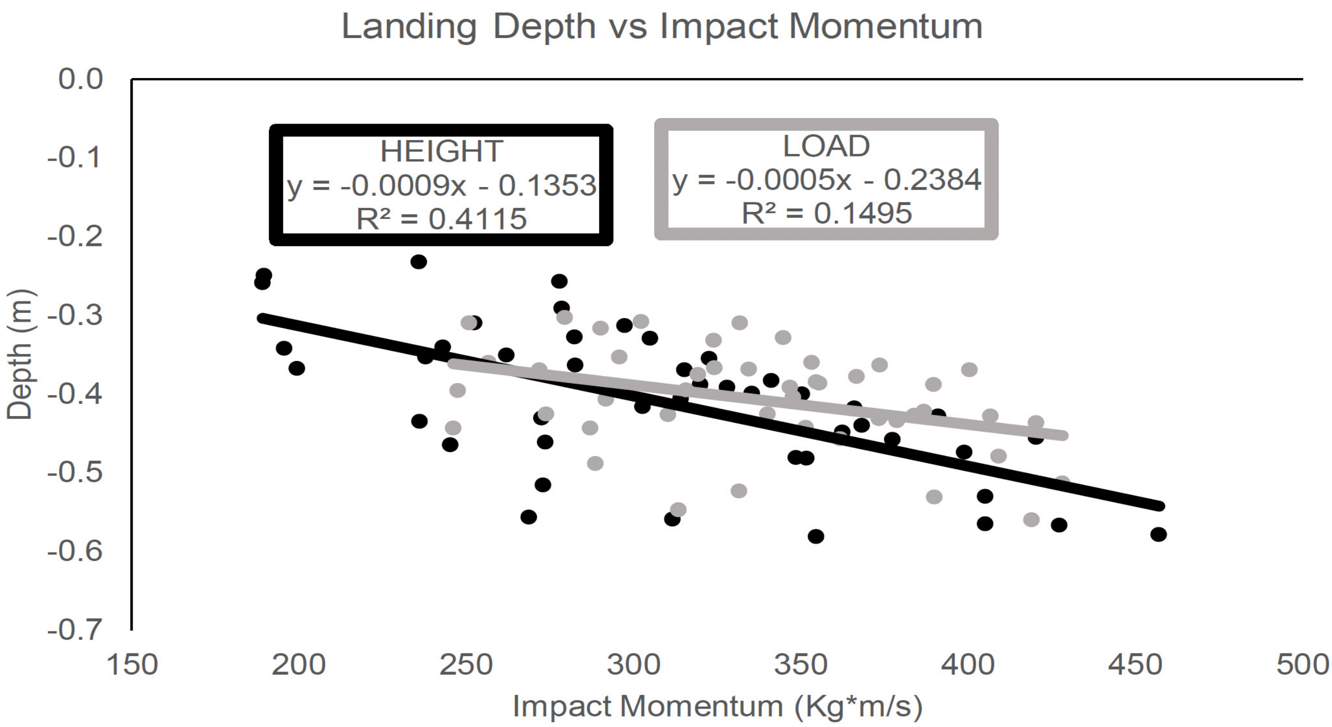

Figure 3. Landing Depth with respect to impact momentum for drop landings increased by HEIGHT (black) and LOAD (gray).

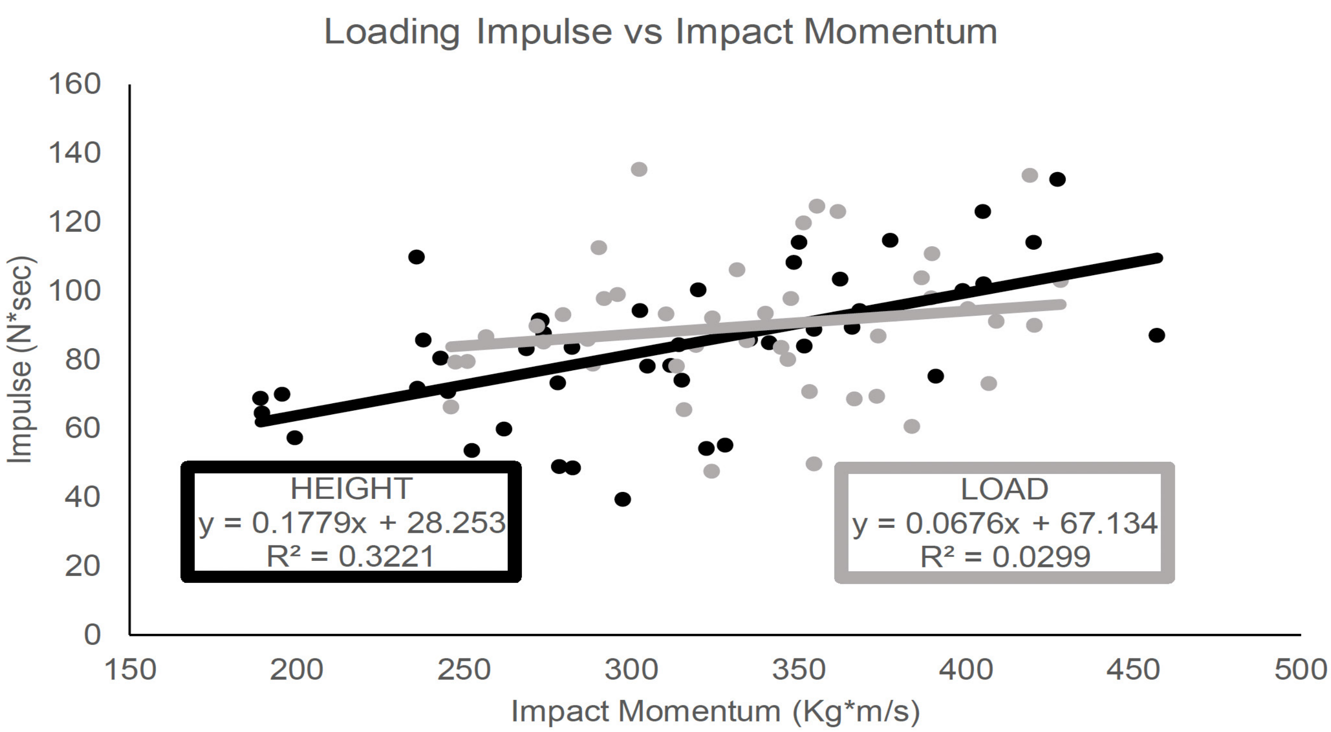

Figure 4. Loading Impulse with respect to impact momentum for drop landings increased by HEIGHT (black) and LOAD (gray).

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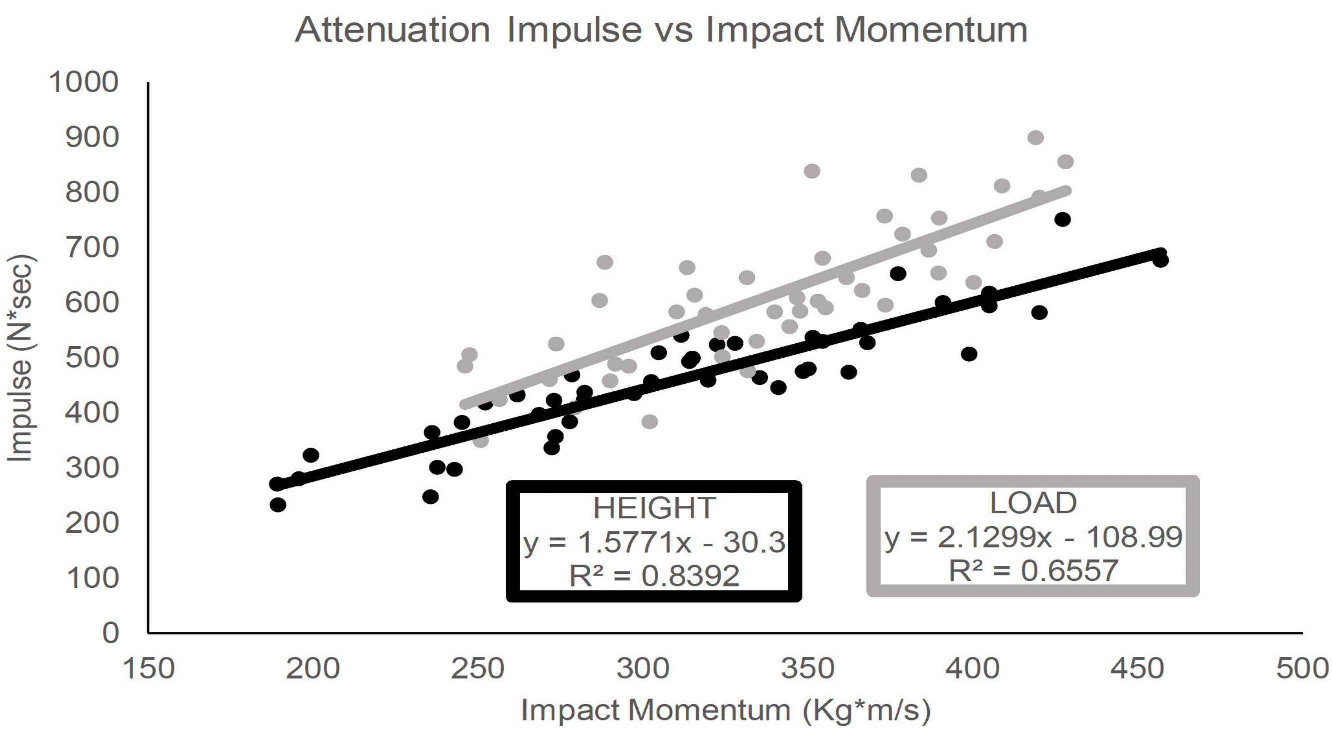

Figure 5. Attenuation Impulse with respect to impact momentum for drop landings increased by HEIGHT (black) and LOAD (gray).

with LOAD. Moderate relationships, identified by regressions with an R2 between 0.3 and 0.5, were loading impulse with HEIGHT, landing depth with HEIGHT, and average vGRF with HEIGHT. Weak relationships, identified by regressions with an R2 less than 0.3, were loading impulse with LOAD, landing depth with LOAD, and average velocity with HEIGHT. Loading impulse and average velocity with LOAD were the only regressions to not be statistically significant, indicating the regression equation did not predict loading impulse or average velocity better than the average across all trials. Weak R2 values indicate significant motor variability among participants while strong R2 predictable mechanical responses to changes in impact momentum. While HEIGHT and LOAD were not statistically compared, overloading the drop landing with HEIGHT and LOAD led to some contrasting responses from the neuromusculoskeletal system. The importance of safe lower extremity alignment during impact and loading to reduce risk of knee injury is well-documented (Hewett et al., 2005, 2016), and previous research suggest the loading impulse should be limited while the attenuation impulse should be maximized (Harry et al., 2018, 2019). In this study, attenuation impulse increased with both HEIGHT and LOAD, while loading impulse presented a moderate positive relationship using HEIGHT but an insignificant relationship with LOAD. Thus, external loading may be an effective means to increase demand on attenuation impulse without accompanying increases in loading impulse. However, high loading impulses are common in plyometric movements like sprinting and jumping in elite sport. So, while performing landing exercises with limited loading impulses may reduce injury risk for a given repetition, it may also fail to stimulate the appropriate neuromusculoskeletal adaptations to prepare competitive athletes for the impact demands of sprinting and jumping.

In research from Earp et al, they observed greater tendon strain with faster movement speeds during loaded squats (Earp et al., 2016). Roberts and Konow demonstrated how tendons buffer energy during muscle tendon unit lengthening such that faster eccentric movements result in an initial stretch of the tendon followed by eccentric muscle action (Roberts & Konow, 2013). The tendon behaves in such a way that reduces the eccentric power demand on the muscle compared to the tendon (Roberts & Konow, 2013). An interesting result of our study was the weak relationships observed between average eccentric velocity with HEIGHT and LOAD. However, average eccentric velocity with LOAD nearly failed normality assumptions and presents with a flatter slope than HEIGHT. Mechanically, HEIGHT (1.22 m for the highest drop condition) increases the impact velocity, which can be observed by a greater (faster) intercept compared to the LOAD (0.61m height for all drops). These results indicate individual and

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between variability requiring further research to better understand why and how people accomplish deceleration. The individual variability may be related to the relationship between eccentric peak power and tendon quality in the lower extremities, allowing participants with greater tendon quality the potential to land faster. Further, since sprinting and jumping require fast stretch-shortening cycle actions, it may be useful for athletes to execute drop landings from supramaximal heights due to the faster eccentric velocity at impact.

Another important consideration is the relative contributions of the lower extremity joints to deceleration. When analyzing the differences in eccentric work during the loading phase (i.e. following a maximal countermovement jump), slower landers used greater contributions from the hip while faster landers used greater contributions from the ankle (Harry et al., 2018). In the attenuation phase, faster landers produced greater eccentric work from the knee joint (Harry et al., 2018). If we take account of these past studies with the current study to generate future research hypotheses, the observed variability may be based on relative contributions among lower extremity joints in our subject pool. Using HEIGHT, with the faster impact velocity, may demand greater contributions from the ankle and knee joints while the LOAD conditions emphasize the hip joint. Future research measuring kinematics and joint kinetics are required to determine if there are unique joint contributions, both acute responses and chronic training adaptations, when impact momentum is administered through HEIGHT or LOAD.

Of course, there are limits to the generalizability of our findings to specific sporting populations. The current study is an acute response to a relatively novel task. Participants in this study were recreationally trained young adults with minimal to no experience performing drop landings with external load or supramaximal heights. One noteworthy result was the absence of injuries in any participants, which should provide confidence that competitive athletes can perform these tasks without undue risk. Advancing the current investigation calls for short term training and eventually long duration exposure to determine how overloading landing tasks can be used to test, develop, and optimize braking capacity, the benefit of which may include both improved performance and durability when performing demanding athletic movements like sprinting, jumping, and changes of direction.

CONFLICTS OF INTEREST

We have no conflicts of interest to disclose.

FUNDING

This study received no specific funding in order to be completed.

ETHICAL APPROVAL

The study protocol and recruitment procedures were approved by the University's Institutional Review Board (protocol #2003296).

DATES OF REFERENCE

Submission - 07/06/2024
Acceptance - 26/03/2024
Publication - 02/01/2026

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