International Journal of Strength and Conditioning

Baus, J., Harry, J. R., & Yang, J. (2024). Weighted Vest Load Arrangement and Data Normalization Effects on Lower Limb Biomechanics During Countermovement Jump Landings. International Journal of Strength and Conditioning
https://doi.org/10.47206/ijsc.v4i1.186

Weighted Vest Load Arrangement and Data Normalization Effects on Lower Limb Biomechanics During Countermovement Jump Landings

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ABSTRACT

This paper assessed the weighted vest load arrangement and data normalization method effects on ground reaction forces (GRF), joint kinematics, and joint kinetics during the landing portion of the countermovement jump. Vertical GRF and sagittal kinematic data were obtained from 12 males and 12 females during countermovement jump-landings in 4 different loading arrangements (unloaded, 10% body mass load placed anteriorly, posteriorly, and split anterior/posterior). Two methods (body mass vs. mass*landing height) were used to normalize joint torques to determine whether common mass-normalization (type A) yielded different results than a jump-landing specific mass*landing height normalization (type B) in statistical significance. Mixed-model analyses of variance (α=0.05) and effect sizes (ES) were used to assess differences between sexes and loading conditions for each normalization method. Results show that for normalization A, significant statistical differences were found between sexes for peak vertical GRF, hip moment, and knee moment. Pooled sex peak vertical GRF and hip moments showed significant differences when comparing the unloaded with the back and front-loaded conditions. For normalization B, the peak vertical GRF also showed significant differences between men and women but with smaller effect sizes. Only the hip moment showed significant differences for both normalization methods but changed the magnitude of its effect sizes. Results suggest that different normalization methods could be considered for joint moments or GRF depending on the nature of the statistical significance of jump height.

Keywords: Weighted vest load; Lower limb kinematics and kinetics; Countermovement jump landings

INTRODUCTION

Maximal effort jumping and consecutive landing movements require a coordinated set of motions between the lower and upper extremities [1], [2]. In general, maximal effort sports movements like running, cutting maneuvers, and jumping contribute to a large percentage of non-contact injuries in athletes. Considering that the jumping-landing motion is widespread in sports like volleyball, basketball, and soccer [3]–[6], different training programs seek to improve jump performance while

also reducing overuse injury risk during landing in amateur and professional players [7], [8]. Training programs use different jumping maneuvers to assess kinematic and kinetic variables. The most common types are the drop vertical jump, the squat jump, and the countermovement jump [9]–[13]. Differences between the countermovement and squat jump have been studied for training programs considering muscle slack and force development [14]. The countermovement jump has some advantages in terms of reliability. It may be easier to perform than the drop vertical jump [15], relatively non-fatiguing, and requires minimal familiarization [16]. Also, it produces greater jump heights than the squat jump because the presence of a countermovement action facilitates more significant muscular force generation over more prolonged periods [2]. The considerably better performance for countermovement jump is greatly defined by the coordinated movement of the shoulder, elbow, hip, knee, and ankle joints [3], [17].

Joint displacements and moments of the hip, knee, and ankle are of interest when assessing the injury risk in non-contact situations [18], [19]. One of the most common injuries in athletes in non-contact situations is the anterior cruciate ligament (ACL) injury. Sex disparity has been reported for ACL injury rates. Regardless of sex, the ACL injury is related to different instances during the landing phase, such as the initial contact with the ground and the instant of maximum knee flexion. Injury to the ACL is due to the excessive ligament strain that occurs when attenuating high-ground reaction forces [20], [21]. Hip, knee, and ankle joints significantly contribute to energy dissipation when landing. Landing with greater hip, knee, and ankle flexion improves energy dissipation [22], [23] and reduces the ACL injury risk. Literature has reported that ground reaction forces (GRFs) increase as external loading is added to the system [19], [24] and the lower limb biomechanics [25]–[28] and its corresponding differences between genders [29]–[32].

Of course, performance and injury risk are closely related, and both need to be considered when developing a training program that induces physical performance and neuromuscular adaptation [33]. Using an external load is a common practice during training to improve jump performance and reduce injury risk [34]. The external load can be applied to the athletes as a weighted vest (WV) by holding dumbbells or using a barbell across the shoulders [35]. In the case of athletes' training and warming-up protocols, it is common to use a 10-15% body weight (BW) to enhance vertical jump height [36], [37]. In comparison, in the case of military training, it has been reported to use 25 – 100% BW as the external load, considering that U.S. soldiers routinely carry around 65% to 75% of the soldier's BW [19], [38]. Weighted vests are typically positioned, so the load is arranged symmetrically over the trunk or upper body [24]. Literature has reported changes in posture and gait patterns with different loading arrangements [39]–[41], showing fewer modifications in biomechanical demand when the load is closer to the hip and the body's center of mass [42], [43].

Different loading magnitudes with fixed loading arrangements have been studied for countermovement jump (CMJ) [44], [45]; however, asymmetrical loading causes different lower extremities biomechanical demands [46]. Altered trunk motions were observed using a weighted vest loading (approximately 10% body mass) such that half of the mass was added symmetrically over the trunk. During landing, increased trunk lean leads to greater hip and knee energy absorption and subsequent reduction in lower extremities injury potential [46]. Given that all jumping actions involve a requisite landing, it is reasonable to presume that manipulating the load arrangement in a weighted vest during countermovement jump landings could influence the joint's mechanical outputs during the landing phase. We assume that the peak vertical GRF during the landing phase could differ depending on the external loading arrangement. This investigation focuses on the landing portion of a CMJ since greater peak vertical GRF during this phase is closely related to lower extremities injury risk.

Besides GRF, we will analyze joint moments during the landing phase. Considering that each participant has a different height, weight, and performance, we consider these factors to compare the hip, knee moments, and GRF properly. Traditionally, two methods have been used, normalizing to body mass [47], [48] and normalizing to body mass and height [2], [3]. In the case of jumping with external loading, literature has reported normalization of joint moments with respect to total mass, including the external loading [31] and normalizing to total mass and jump height [49]. In the case of GRF, previous studies have shown how they depend on jump height [26], which is another relevant factor to consider when normalizing the data from countermovement jumps [50].

The purpose of this study was, first, to investigate

knee and hip flexion angles and joint moments for different load arrangements (back-loaded, front-loaded, split-loaded, and unloaded) of weighted vests based on inverse kinematics and inverse dynamics analysis in an OpenSim musculoskeletal model [51]–[54]. Second, to determine whether the effect of these arrangements on the GRF magnitude is different between male and female subjects. Third, to compare the statistical difference when using different normalization methods for joint moments and GRF. We hypothesized that there would be a significant difference in the magnitude of GRFs for the unloaded condition than the other conditions due to less weight on the system. Also, it was hypothesized that there would be significantly different joint flexion angles and joint moments for the hip and knee when comparing men and women due to the different landing strategies. Finally, we expect to find similar statistical differences between sex and loading conditions regardless of the normalization method.

METHODS

Participants

G*Power 3.1 software [55], [56] was used to perform an a priori t-test for the difference between two independent means power analyses with jump height data from a previous study [35] to determine the necessary sample size. This analysis indicated that 24 participants were required to achieve a proposed effect size of 0.70, a power (1-β) of 0.90, and an alpha (α) of 0.05. A sample of 24 healthy adults (26.13 ± 3.33 years), 12 males (88.75 ± 16.36 Kg; 1.77 ± 0.07 m), and 12 females (62.67 ± 10.32 Kg; 1.65 ± 0.06 m) were recruited to participate in this research. The participants defined themselves as "recreationally active" due to their active participation in recreational sports or exercise routines that required jumping and landing maneuvers for at least six months before the start of this study. None of the participants had any condition or injury that would have limited their ability to perform maximum effort and had no recent history (≤ 1 year) of significant injury to the lower extremities. The experimental protocol has been approved, and ethical approval has been obtained by Institutional Review Board (IRB) with protocol number 864667-3 at the data collection site. Informed consent was provided to the researchers.

Experimental Protocol

Participants completed a single laboratory session where demographic and anthropometric measures were first recorded (age, gender, height, mass), and a protocol demonstration was provided. Clarification of the protocol was provided as needed throughout the data collection. Participants were given appropriate-sized athletic shoes (Vazee Pace v2; New Balance Athletics, Inc., Boston, MA) worn during all laboratory activities to control potential footwear effects. Participants completed a standardized warm-up protocol consisting of five minutes of walking and jogging on a treadmill at a self-selected pace, followed by the performance of five CMJ. All five CMJ attempts were separated by approximately 30 seconds and ranged in intensity from moderate to maximum.

After completing the warm-up, participants performed eight maximum effort CMJ during four experimental conditions. Each condition was performed with the participants wearing a weighted vest (Mir Vest, Inc., San Jose, CA, USA) configured in the following ways: zero added mass (Unloaded), 10% body mass added symmetrically over the trunk (Split-loaded), 10% body mass added over the anterior aspect of the trunk (Front-loaded), and 10% body mass added over the posterior aspect of the trunk (Back-loaded). The four conditions were presented such that the unloaded condition was performed first, after which the split-loaded, front-loaded, and back-loaded conditions were presented in a counterbalanced order, so the load arrangements were delivered randomly for each participant.

A 10-camera motion capture system (Vicon Motion Systems, Ltd., Oxford, UK; 200 Hz) was used to obtain three-dimensional kinematic data. Reflective spherical markers (14 mm) were adhered bilaterally to the participants' trunk and lower extremities at the following locations: acromion process, iliac crest, anterior superior iliac spine, posterior superior iliac spine, medial and lateral aspects at the knee, and the medial and lateral malleoli. Individual markers were also placed on the C7 vertebrae, the sternoclavicular notch, and the sacrum. Posteriorly, three-marker cluster sets adhered bilaterally over the calcaneus. Finally, four-marker cluster sets adhered bilaterally to the lateral aspect of the thigh and shank. Three-dimensional GRF data were obtained synchronously to the kinematic data using a dual force platform system (Kistler Instruments, Corp., Amherst, NY; 1000 Hz).

Each trial began with the participants standing motionless in a two-footed position, with each foot

on a force platform. For each trial, the participants used a self-selected countermovement depth, as depth changes could reflect a response to the load arrangements. In addition, participants were free to use a preferred arm swing strategy because we sought to study mechanics during maximum performance jumps. Each foot had to contact a force platform when landing, and the participant was required to return to a motionless standing position. A trial was discarded and repeated in the following scenarios: the jump appeared submaximal effort, the participant could not land with each foot contacting an individual force platform, or could not return to a motionless standing position. No participant required more than 35 trials to perform 32 successful trials across the four conditions.

Data Processing

OpenSim platform [57], [58] was used for data processing and analysis. The subject-specific musculoskeletal models were generated by scaling a three-dimensional gait model (Gait 2354) with 14 segments, 23 degrees of freedom, 54 muscles, and no upper extremities [51]–[54]. Note that we did not collect upper extremities' motion data in the experimental data collection. Therefore, the musculoskeletal model did not have upper extremities either. The OpenSim pipeline used in this paper includes the scaling, inverse kinematics, and inverse dynamics tools available in the software. This pipeline was proven valid and effective in previous literature [59], where the use of the reduced residuals and computed muscle control tools is included. The scaling process was done by adjusting each participant's height, weight, and estimated inertial properties. After the scaling process, inverse kinematics (IK) analysis was conducted. The markers from the motion capture data matched the virtual markers on the model used. This process obtained the joint kinematics by reducing the error between the position of the virtual and physical markers during the jumping-landing task [60]. The joint kinematics and GRF data were used to perform inverse dynamics (ID). The weighted vest mass was not added to the model as an external load to run ID, and it was assumed that it would not change the trunk's inertia or center of mass at the moment of obtaining the internal joint moments. We defined the flexion moment as positive for knee and hip joints. For this process, the GRF data were smoothed using a Butterworth filter with a cut-off frequency of 6 Hz.

The results from IK and ID were then exported to MATLAB®, where the jumping-landing motion was divided into three global phases. The first phase was the time from the onset movement to take-off. The second was the flight phase (take-off to ground contact). The third was the landing phase [16]. Specifically, the vertical GRFs from the right and left force plates were summed to represent the overall GRF of the system. Then, the first phase was defined from the first frame (beginning of the weighting phase) until the vertical GRF was less than 5N. The second phase was defined one frame after the first period until the frame where the vertical GRF was greater than 5N. The last phase was defined one frame after the ending of the second period through the end of motion when the participant returned to a standing position. Since the sampling rate differed between the force plates and the motion capture data, a simple linear transformation was done to map the frames obtained from the GRF data to the IK and ID data.

Furthermore, the maximum flexion angle and moment were obtained for the knee and hip joints, as was the peak vertical GRF during the landing phase. The peak vertical GRF was calculated from the summed vertical GRF data of the two force plates to properly represent the total GRF acting on the body's center of mass [31]. For the kinematics analysis, only the right limb data was used since it has been shown that asymmetries in sagittal joint angular displacements and vertical GRF are unlikely [49], [61], [62].

As stated, previous studies have used participant body mass or body mass times standing height [2], [3], [47], [48] to normalize the joint moments' and GRF data during landings with added mass from consistent heights [63] or when samples are pooled by sex [64]. However, as mentioned in the introduction, a more appropriate normalization approach is needed for jump-landings with and without added mass because the fall height before impact can differ when accommodating the added mass or a novel mass arrangement. As such, we used two normalization approaches to determine whether the results of the study change by way of data normalization. We define normalization A as the method where the joint moments and GRF are normalized to the participants' systems mass [31]. On the other hand, normalization B is defined as the joint moment, and GRF values are normalized to the system mass multiplied by landing height [49]. Landing height values were obtained in a previous study [65].

Statistical Analysis

Mean values and standard deviation (SD) were calculated across trials per participant for each loading condition. Five mixed-model factorial analyses of variance (α=0.05) were carried out in IBM SPSS Statistics software (v29; IBM Corp., Armonk, NY), with sex as the between factor and loading condition as the within factor. If a significant interaction was detected, an independent sample t-test was used to assess sex differences for each loading condition. Also, a paired-sample t-test was used to evaluate differences between any pair of loading conditions among males and females. The Sidak adjustment was used to compare the main effects when no significant interaction was detected. The Shapiro-Wilk test was used to assess the normality of the data. To identify the presence of a meaningful effect [66], Cohen's d effect sizes (ES) were obtained to normalize the magnitudes of the mean differences. The ES values were interpreted using Sawilowsky's [67] scale (very small: ES<0.2, small: 0.2≤ES<0.5, medium: 0.5≤ES<0.8, large: 0.8≤ES<1.2, very large: 1.2≤ES<2.0, and huge: ES≥2.0). The statistical process was conducted identically for both normalization methods.

RESULTS

No significant interactions were detected for hip (p=0.265) and knee flexion angles (p=0.226). Neither normalization A nor B showed significant interactions for the peak vertical GRF (p=0.550, p=0.405), hip (p=0.678, p=0.497), and knee (p=0.828, p=0.723) moments. Consequently, main effects were assessed for differences between sexes with pooled load condition data and among loading conditions with pooled sex data.

Sex effects

Sex data are presented in Table 1. Large sex differences were detected, with greater peak vertical GRF (p=0.006, ES=0.92) and greater hip moments for normalization A (p=0.006, ES=1.04) in men compared to women. A medium difference was detected for knee moment, with a greater magnitude displayed by men versus women for normalization A (p=0.009, ES=0.66). A medium significant difference was found for peak vertical GRF (p=0.045, ES=0.62) in the case of normalization B. No significant differences between men and women were found for hip (p=0.673, ES=0.18) and knee flexion angles (p=0.781, ES=0.11) or hip (p=0.404, ES=0.30) and knee (p=0.150, ES=0.34) moments for normalization B when collapsed across loading conditions.

Load Condition effects

Load condition data are presented in For normalization B, a medium difference was found for the hip moment (p=0.027, ES=0.71) between the back-loaded and unloaded conditions. Similarly, large and medium differences were detected for the knee moment between the back-loaded and front-loaded conditions (p=0.029, ES=0.62) and when comparing the back-loaded and split-loaded conditions (p=0.009, ES=0.86).

Table 1. Differences between Men and Women

Variables	Men		Women			
	Mean	SD	Mean	SD	*p*	ES
Hip Flexion Angle	72.34	32.20	67.74	20.45	0.673	0.18
Knee Flexion Angle	98.28	16.15	96.73	12.82	0.781	0.11
Normalization A						
Peak Vertical GRF*	23.21	6.14	18.39	4.67	0.006	0.92
Hip Moment*	4.51	2.11	2.75	1.35	0.006	1.04
Knee Moment*	2.47	1.10	1.92	0.54	0.009	0.66
Normalization B						
Peak Vertical GRF*	47.70	11.16	54.67	12.26	0.045	0.62
Hip Moment	9.32	4.37	8.15	3.89	0.404	0.30
Knee Moment	5.08	2.36	5.72	1.52	0.150	0.34

*Note: Units of measurement for Peak Vertical GRF for Normalization A (N Kg^{-1}), Normalization B (N Kg^{-1} m^{-1}), hip and knee flexion angle (°), hip and knee moments for Normalization A (N m Kg^{-1}), Normalization B (N m Kg^{-1}) m^{-1}); Mean: average across participants; SD: ± one standard deviation; p=statistical probability; ES = Cohen's d effect size; * significant difference between men and women (p<0.05).*

Table 2. Differences between Loading Conditions

Variables	Back-loaded		Front-loaded		Split-loaded		Unloaded		
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	*p*
Hip Flexion Angle	66.66	29.53	71.75	27.22	72.50	26.13	69.26	26.03	0.172
Knee Flexion Angle	97.92	14.29	99.51	15.98	98.23	13.75	94.34	14.40	0.091
Normalization A									
Peak Vertical GRF†‡	18.85	4.71	19.94	6.69	20.44	6.07	23.98	5.12	<0.001
Hip Moment †‡	2.93	1.23	3.42	1.89	3.70	1.84	4.46	2.45	0.001
Knee Moment	2.18	0.64	1.94	0.46	1.92	0.49	2.74	1.43	0.001
Normalization B									
Peak Vertical GRF	48.30	8.93	50.42	13.44	50.57	13.85	55.50	11.45	0.083
Hip Moment †	7.38	2.78	8.47	3.96	8.93	4.25	10.16	5.08	0.008
Knee Moment §¶	5.57	1.23	4.94	0.86	4.70	0.84	6.38	3.43	0.013

Note: Units of measurement for Peak Vertical GRF (N Kg^{-1}), hip and knee flexion angle (°), hip and knee moments for Normalization A (N m Kg^{-1}), Normalization B (N m Kg^{-1} m^{-1}); Mean: average across participants; SD: ± one standard deviation; p=statistical probability; † significant difference between unloaded and back-loaded conditions (p<0.05), ‡ significant difference between unloaded and front-loaded conditions (p<0.05), § significant difference between front-loaded and back-loaded conditions (p<0.05), ¶ significant difference between split-loaded and back-loaded conditions (p<0.05).

Table 2. Considering that the effect size quantifies the size of the mean differences between two variables, it is calculated only for the pair of loading conditions that showed a significant difference. Significant differences were detected for the peak vertical GRF when collapsed across sex. Notably, this only happened for normalization A where large and medium loading condition differences were detected, with greater peak vertical GRF for the unloaded condition when compared to the back-loaded condition (p=0.001, ES=1.09) and the front-loaded condition (p=0.028, ES=0.71), respectively. In the case of the hip joint, there are large and medium significant differences with a greater moment for the unloaded condition in contrast with the back-loaded condition (p=0.004, ES=0.81) and the front-loaded condition (p=0.006, ES=0.50), for normalization A. For normalization B, a medium difference was found for the hip moment (p=0.027, ES=0.71) between the back-loaded and unloaded conditions. Similarly, large and medium differences were detected for the knee moment between the back-loaded and front-loaded conditions (p=0.029, ES=0.62) and when comparing the back-loaded and split-loaded conditions (p=0.009, ES=0.86).

DISCUSSION

This study aimed to determine whether using different load arrangements as a WV during the landing phase of a countermovement jump alters the GRF, kinematic and kinetic variables for the hip and knee joints in men and women. Following our first hypothesis, we observed a greater magnitude in the peak vertical GRF when compared to the unloaded with the back-loaded and front-loaded conditions but only for normalization A. There was no significant difference between the unloaded and the split-loaded condition, possibly because there was no need to accommodate an asymmetric mass and inertial characteristics, as it is better distributed over the participant's trunk [31]. In agreement with previous work [49], the peak vertical GRF was smaller in the presence of an additional load as lower jump heights were achieved. In the case of our study, we found a similar behavior for all the loading arrangements (back-loaded, front-loaded, and split-loaded) compared to the unloaded condition. Other studies also show this behavior because an increased system mass reduces the maximum jump height [38], [68]. Previous studies have reported a 5-10% increase in GRFs [63], [69], [70] in the case of drop jump landings, where jump height does not need to be considered for normalization since the landing height is fixed. When comparing male to female jumpers, it has been reported that females withstand higher GRF due to lesser lower limb stiffness [25], which is the opposite of our results. It has to be considered that previous studies have reported differences in vertical jump heights for females when compared to male jumpers [65], [71], so that factor motivated us to take two strategies at the time of normalizing the data.

For the case of sex differences, we can see in Table 1 that including the jump height as a normalization factor (normalization B) causes no significant

difference in either the hip moment or the knee moment. This change in the significance is caused by the fact that jump height shows a huge significant difference (p<0.001, ES=2.22) when comparing men and women [65]. On top of that, the effect sizes reduced considerably since the standard deviation in both cases increased. As shown in Figures 1, 2, and 3, the data for sex difference is more dispersed in the case of normalization B when compared to normalization A. Besides the increase in standard deviation, in almost all cases for both loading and sex conditions, the effect of outliers is increased for normalization method B. This change in the magnitude and significance of this difference shows that in the case of comparing sex with the pooled loaded condition, landing height should be considered for the normalization.

In the case of loading condition, Table 2 shows a different trend than the sex differences. For the case of hip moment, we can still see a significant difference for both normalization methods when comparing the back-loaded and unloaded conditions. Similar to the case of sex differences, the effect size got reduced for normalization B. Interestingly, for normalization method B, we can now find medium and large significant differences for knee moment. Similarly, in comparison between sexes, we can still see an increase in the standard deviation for normalization B, which is consistent with the fact that jump height is a dispersed variable among participants. Unlike the previous case, for loading conditions with pooled sex comparison, the differences are only small and very small [65]. This contrast makes us believe that there should be further consideration when using or not the landing height as a normalization factor. One factor to consider could be the magnitude and significance of the variable that is being analyzed. We can relate this statistical significance of landing height to the difference in mechanical energy for the variable being analyzed with or between factors like sex and external loading [30], [72].

When exploring the differences among loading conditions and sex (Tables 1 and 2), it was evident that there was an increase in the GRF with a higher peak hip flexion moment [73]. Previous literature demonstrated increased knee flexion angle during landing for men compared to women in loaded and unloaded cases, but our results in Table 1 did not show a significant difference for this parameter [22], [70]. Previous studies have reported greater energy absorption and lesser ACL injury risk with greater knee flexion. Given what was stated previously and

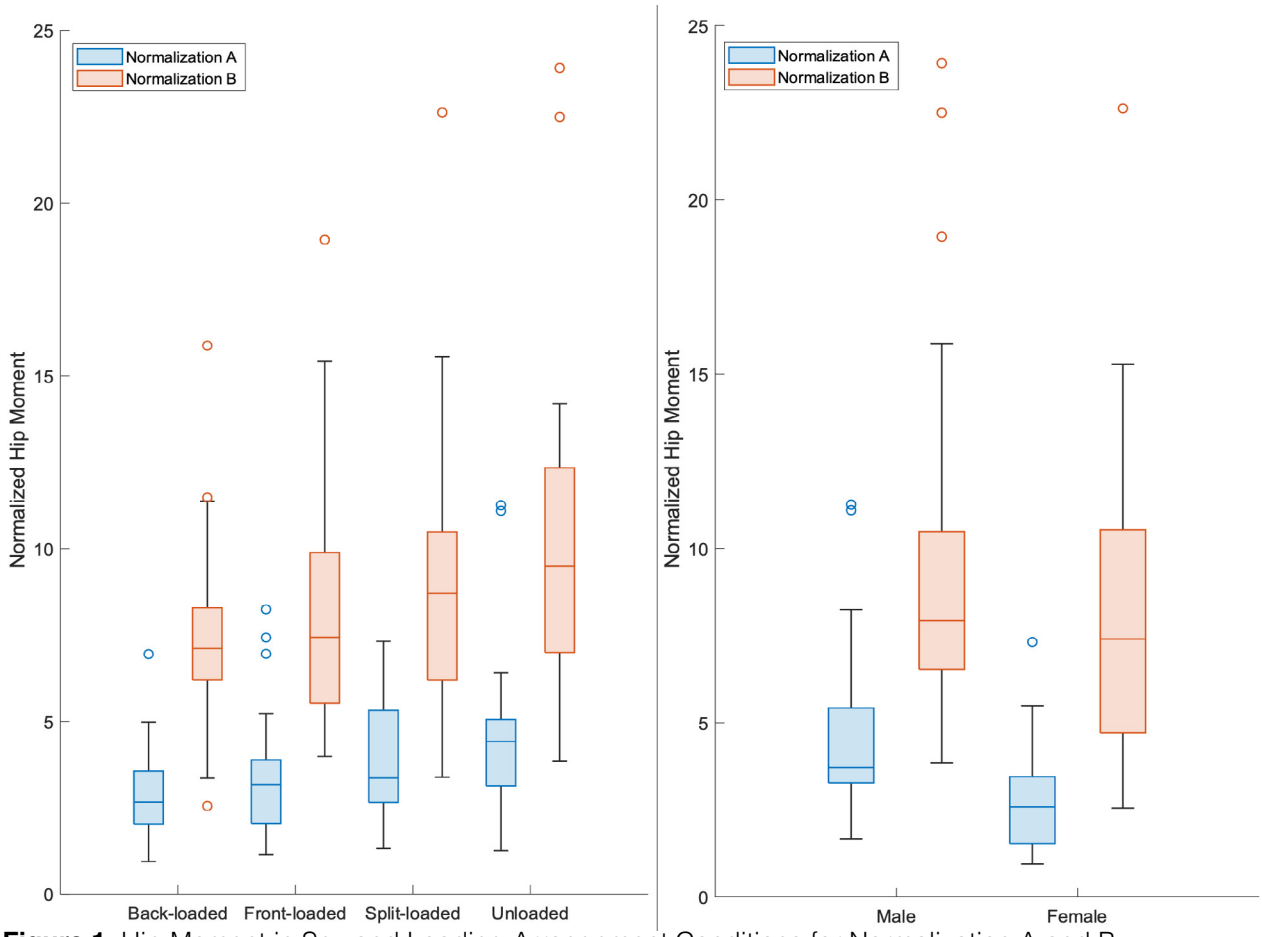

Figure 1. Hip Moment in Sex and Loading Arrangement Conditions for Normalization A and B.

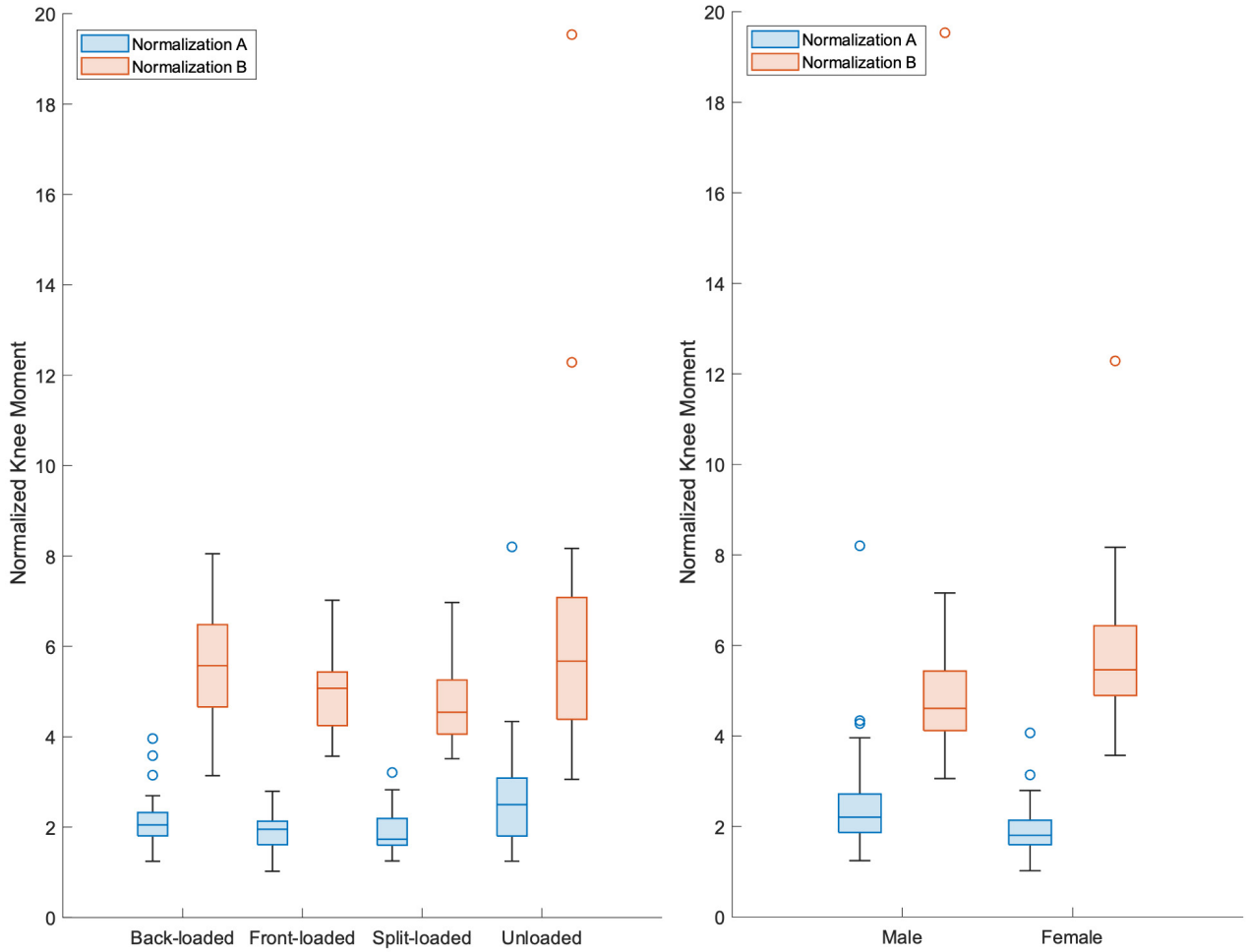

Figure 2. Knee Moment in Sex and Loading Arrangement Conditions for Normalization A and B.

the fact that the female landing strategy appears ligament dominant [29], there may be an excessive ligament strain and, consequently, increased ACL injury risk in females [20], [21].

Our second hypothesis was partially supported since there were significant differences for knee and hip joint moments but not for flexion angles. This response could be different if the participants were asked to jump at a maximum speed instead of jumping to reach a maximum height [26]. On the other hand, the added mass to the system was thought to produce a higher biomechanical demand that could cause a movement solution during the landing phase in response to the addition of an external stressor [74], [75]. The smaller relative GRF did not show this accommodation strategy, but it has to be considered that load and jumping height affects the biomechanical demand [49]. For that reason, we could be looking at a higher joint moment for men compared to women and for the unloaded condition compared to the other loading arrangements. Anyhow, since the joint flexion angle is not statistically significant, these joint moments should be analyzed from a different perspective where muscle activity and energy absorption strategies are considered [1], [35], [46]. A training program designed to improve jump performance with external loading must consider that increasing maximal strength relative to body mass improves explosiveness in lower body movements [76]. With this idea in mind, the percentage of body weight added to each athlete should be personalized based on their joint strength. Assuming that maximal strength and maximal functional strength are known quantities, heavier-weighted vests could be used with stronger athletes.

From an ergonomics standpoint, loaded and unloaded jumping could cause loss of stature, muscular fatigue, and injuries in the lower back due to repeated impacts [77], [78]. In terms of injury risk, a limitation of this study was the lack of tracking for kinematic and kinetic data for the ankle joint because its behavior contributes to the landing mechanics, and the ankle sprain is another relevant injury in non-contact situations. Consecutive studies could analyze the same kinematic and kinetic variables over the countermovement jump phases, including the flight time and maximum jump height [79]. Another limitation to note is the small sample size, which was convenient for doing a study with five likely correlated dependent variables. Another factor to consider is that participants were free to

perform the arm swing in the most comfortable strategy. Even when the arm swing modifies the countermovement jump kinematic variables [80], it is suggested to complete the jump without an arm swing [81]. The mentioned effects are only preliminary evidence to hypothesize the injury risk in lower extremities, but they should be explored and confirmed with future studies. Additionally, prospective studies could consider the effect of analyzing the differences between dominant and non-dominant limbs. It has been reported that the injury risk varies with kinematic and kinetic variables in the lower extremities, with higher ACL injury risk in the non-dominant leg for athletes [82]–[84].

CONCLUSION

This study showed vertical GRF, knee, and hip moments adjustment to front-loaded and back-loaded arrangements during the countermovement jump. Large differences for peak GRF were observed to be greater for men when pooled loading condition data and for the unloaded condition when pooled sex data, using a standard mass normalization. With either pooled sex or loading condition, we did not see a significant difference in the peak hip and flexion angles during landing. To properly compare joint moments, it is necessary to pick a suitable normalization method that considers the statistical significance of the variables being compared. Our results suggest that considering jump height as a normalization factor is appropriate when comparing sex since it shows a significant difference with a great magnitude between men and women. However, the small differences in jump height for different loading arrangements propose a normalization that only considers the participants' system mass. The different added load arrangements may be used in different ways depending on the user's needs in terms of performance. The load accommodation strategy should be considered to allow for appropriate energy absorption and reduce the injury risk in the lower limb.

ACKNOWLEDGMENTS

The National Strength & Conditioning Association (NSCA) Foundation and the Distinguished Graduate Student Fellowship from the Graduate School at Texas Tech University partially supported this work. These agencies did not contribute to the design, analysis, interpretation of results, or the decision to publish this work.

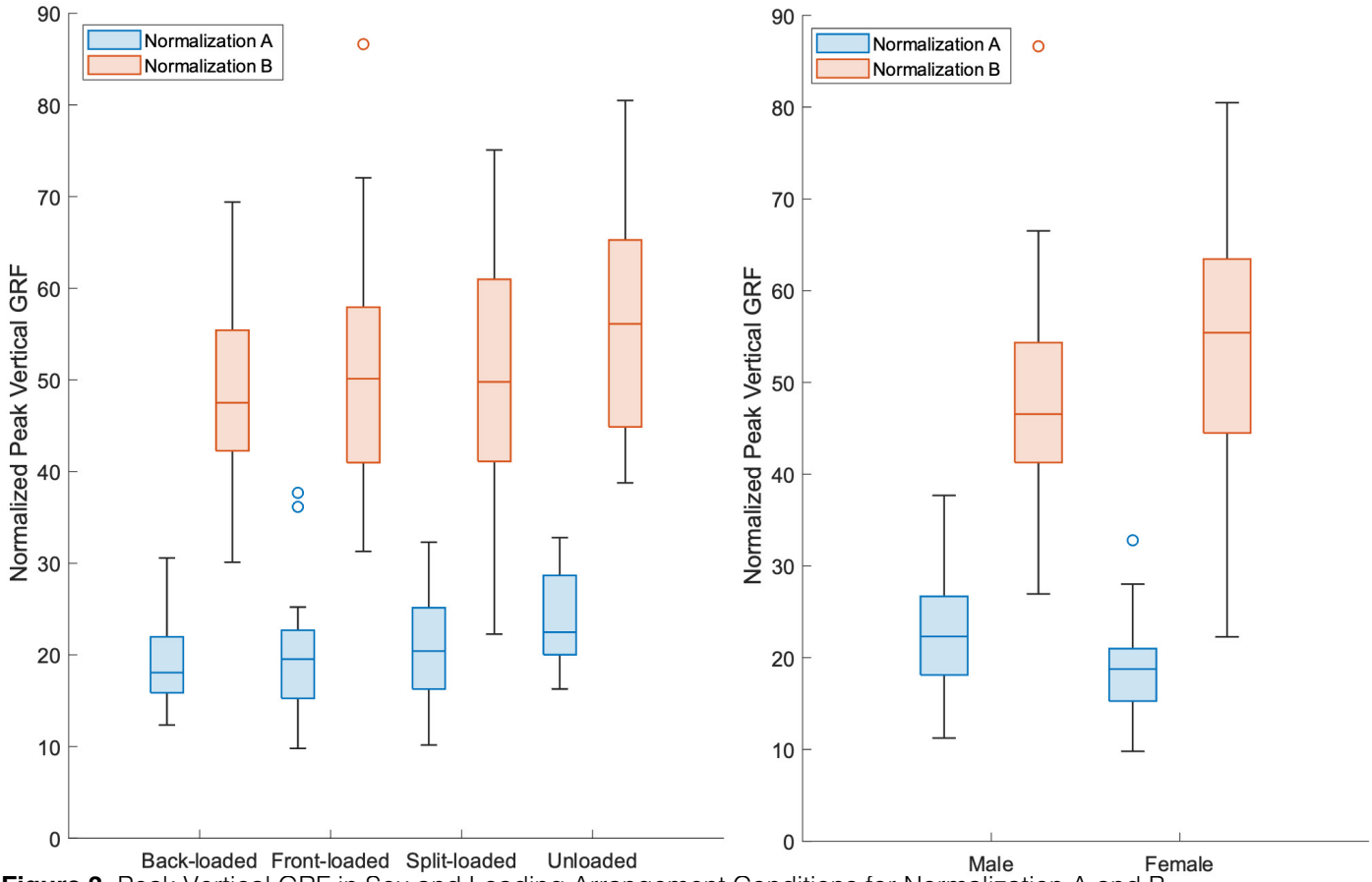

Figure 3. Peak Vertical GRF in Sex and Loading Arrangement Conditions for Normalization A and B.

CONFLICT OF INTEREST

There is no conflict of interest for all authors.

REFERENCES

1. A. Vanezis and A. Lees, "A biomechanical analysis of good and poor performers of the vertical jump," Ergonomics, vol. 48, no. 11–14, pp. 1594–1603, Sep. 2005, doi: 10.1080/00140130500101262.
2. Z. J. Domire and J. H. Challis, "The influence of squat depth on maximal vertical jump performance," J Sports Sci, vol. 25, no. 2, pp. 193–200, Jan. 2007, doi: 10.1080/02640410600630647.
3. G. Hughes and J. Watkins, "Lower Limb Coordination and Stiffness During Landing from Volleyball Block Jumps," Research in Sports Medicine, vol. 16, no. 2, pp. 138–154, Jun. 2008, doi: 10.1080/15438620802103999.
4. J. Rauch, E. Leidersdorf, T. Reeves, L. Borkan, M. Elliott, and C. Ugrinowitsch, "Different Movement Strategies in the Countermovement Jump Amongst a Large Cohort of NBA Players," Int J Environ Res Public Health, vol. 17, no. 17, p. 6394, Sep. 2020, doi: 10.3390/ijerph17176394.
5. H. Arianasab, F. Mohammadipour, and M. Amiri-Khorasani, "Comparison of knee joint kinematics during a countermovement jump among different sports surfaces in male soccer players," Science and Medicine in Football, vol. 1, no. 1, pp. 74–79, Jan. 2017, doi: 10.1080/02640414.2016.1254811.
6. F. J. Rojas, M. Cepero, A. Ona, and M. Gutierrez, "Kinematic adjustments in the basketball jump shot against an opponent," Ergonomics, vol. 43, no. 10, pp. 1651–1660, Oct. 2000, doi: 10.1080/001401300750004069.
7. C. Bosco et al., "The influence of extra load on the mechanical behavior of skeletal muscle," Eur J Appl Physiol Occup Physiol, vol. 53, no. 2, pp. 149–154, Oct. 1984, doi: 10.1007/BF00422578.
8. J. R. Harry, L. A. Barker, R. James, and J. S. Dufek, "Performance Differences Among Skilled Soccer Players of Different Playing Positions During Vertical Jumping and Landing," J Strength Cond Res, vol. 32, no. 2, pp. 304–312, Feb. 2018, doi: 10.1519/JSC.0000000000002343.
9. S. Fukashiro and P. Komi, "Joint Moment and Mechanical Power Flow of the Lower Limb During Vertical Jump," Int J Sports Med, vol. 08, no. S 1, pp. S15–S21, Mar. 1987, doi: 10.1055/s-2008-1025699.
10. K. R. Ford, A. D. Nguyen, E. J. Hegedus, and J. B. Taylor, "Vertical jump biomechanics altered with virtual overhead goal," J Appl Biomech, vol. 33, no. 2, pp. 153–159, Apr. 2017, doi: 10.1123/jab.2016-0179.
11. K. R. Ford et al., "Use of an Overhead Goal Alters Vertical Jump Performance and Biomechanics," 2005.
12. J. D. Simpson, B. L. Miller, E. K. O'Neal, H. Chander, and A. C. Knight, "Ground reaction forces during a drop vertical jump: Impact of external load training," Hum Mov Sci, vol. 59, pp. 12–19, Jun. 2018, doi: 10.1016/j.humov.2018.03.011.
13. A. Sánchez-Sixto, A. Harrison, and P. Floría, "Larger Countermovement Increases the Jump Height of Countermovement Jump," Sports, vol. 6, no. 4, p. 131, Oct. 2018, doi: 10.3390/sports6040131.
14. Ž. Kozinc, J. Žitnik, D. Smajla, and N. Šarabon, "The difference between squat jump and countermovement jump in 770 male and female participants from different sports," Eur J Sport Sci, vol. 22, no. 7, pp. 985–993, Jul. 2022, doi: 10.1080/17461391.2021.1936654.
15. L. A. Barker, J. R. Harry, and J. A. Mercer, "Relationships Between Countermovement Jump Ground Reaction Forces and Jump Height, Reactive Strength Index, and Jump Time," J Strength Cond Res, vol. 32, no. 1, pp. 248–254, Jan. 2018, doi: 10.1519/JSC.0000000000002160.
16. J. J. McMahon, T. J. Suchomel, J. P. Lake, and P. Comfort, "Understanding the Key Phases of the Countermovement Jump Force-Time Curve," Strength Cond J, vol. 40, no. 4, pp. 96–106, Aug. 2018, doi: 10.1519/SSC.0000000000000375.
17. J. J. McMahon, S. Murphy, S. J. E. Rej, and P. Comfort, "Countermovement-Jump-Phase Characteristics of Senior and Academy Rugby League Players," Int J Sports Physiol Perform, vol. 12, no. 6, pp. 803–811, Jul. 2017, doi: 10.1123/ijspp.2016-0467.
18. A. Mitchell, C. Holding, and M. Greig, "The Influence of Injury History on Countermovement Jump Performance and Movement Strategy in Professional Soccer Players: Implications for Profiling and Rehabilitation Foci," J Sport Rehabil, vol. 30, no. 5, pp. 768–773, Jul. 2021, doi: 10.1123/jsr.2020-0243.
19. T. C. Sell et al., "Minimal Additional Weight of Combat Equipment Alters Air Assault Soldiers' Landing Biomechanics," Mil Med, vol. 175, no. 1, pp. 41–47, Jan. 2010, doi: 10.7205/MILMED-D-09-00066.
20. M. Leppänen et al., "Stiff Landings Are Associated With Increased ACL Injury Risk in Young Female Basketball and Floorball Players," Am J Sports Med, vol. 45, no. 2, pp. 386–393, Feb. 2017, doi: 10.1177/0363546516665810.
21. J. T. Weinhandl and K. M. O'Connor, "Influence of ground reaction force perturbations on anterior cruciate ligament loading during sidestep cutting," Comput Methods Biomech Biomed Engin, pp. 1–9, Aug. 2017, doi: 10.1080/10255842.2017.1366993.
22. K. N. S. K. Syamimi, M. S. Salim, and N. Omar, "A biomechanical analysis of the knee during jump landing," 30th Annual Conference of Biomechanics in Sports, no. 39, pp. 265–268, 2012.
23. C. H. Yeow, P. V. S. Lee, and J. C. H. Goh, "An investigation of lower extremity energy dissipation strategies during single-leg and double-leg landing based on sagittal and frontal plane biomechanics," Hum Mov Sci, vol. 30, no. 3, pp. 624–635, Jun. 2011, doi: 10.1016/j.humov.2010.11.010.
24. F. Vaverka et al., "The Influence of an Additional Load

on Time and Force Changes in the Ground Reaction Force During the Countermovement Vertical Jump," J Hum Kinet, vol. 38, pp. 191–200, Sep. 2013, doi: 10.2478/hukin-2013-0059.
25. B. Yu, C.-F. Lin, and W. E. Garrett, "Lower extremity biomechanics during the landing of a stop-jump task," Clinical Biomechanics, vol. 21, no. 3, pp. 297–305, Mar. 2006, doi: 10.1016/j.clinbiomech.2005.11.003.
26. B. Dai, W. E. Garrett, M. T. Gross, D. A. Padua, R. M. Queen, and B. Yu, "The effect of performance demands on lower extremity biomechanics during landing and cutting tasks," J Sport Health Sci, vol. 8, no. 3, pp. 228–234, May 2019, doi: 10.1016/j.jshs.2016.11.004.
27. N. R. Heebner et al., "Landing Kinematics and Kinetics at the Knee During Different Landing Tasks," J Athl Train, vol. 52, no. 12, pp. 1101–1108, Dec. 2017, doi: 10.4085/1062-6050-52.11.25.
28. P. Devita and W. A. Skelly, "Effect of landing stiffness on joint kinetics and energetics in the lower extremity.," Med Sci Sports Exerc, vol. 24, no. 1, pp. 108–15, Jan. 1992.
29. T. E. Hewett, K. R. Ford, B. J. Hoogenboom, and G. D. Myer, "Understanding and preventing acl injuries: current biomechanical and epidemiologic considerations - update 2010.," N Am J Sports Phys Ther, vol. 5, no. 4, pp. 234–51, 2010.
30. J. T. Weinhandl, B. S. Irmischer, and Z. A. Sievert, "Sex differences in unilateral landing mechanics from absolute and relative heights," Knee, vol. 22, no. 4, pp. 298–303, Sep. 2015, doi: 10.1016/j.knee.2015.03.012.
31. J. R. Harry, L. A. Barker, and M. R. Paquette, "Sex and acute weighted vest differences in force production and joint work during countermovement vertical jumping," J Sports Sci, vol. 37, no. 12, pp. 1318–1326, Jun. 2019, doi: 10.1080/02640414.2018.1557825.
32. J. McMahon, S. Rej, and P. Comfort, "Sex Differences in Countermovement Jump Phase Characteristics," Sports, vol. 5, no. 1, p. 8, Jan. 2017, doi: 10.3390/sports5010008.
33. J. A. Wills, D. J. Saxby, D. J. Glassbrook, and T. L. A. Doyle, "Load-Carriage Conditioning Elicits Task-Specific Physical and Psychophysical Improvements in Males," J Strength Cond Res, vol. 33, no. 9, pp. 2338–2343, Sep. 2019, doi: 10.1519/JSC.0000000000003243.
34. J. A. Wills, D. J. Saxby, G. K. Lenton, and T. L. A. Doyle, "Ankle and knee moment and power adaptations are elicited through load carriage conditioning in males," J Biomech, vol. 97, p. 109341, Dec. 2019, doi: 10.1016/j.jbiomech.2019.109341.
35. I. Janssen, J. M. Sheppard, A. A. Dingley, D. W. Chapman, and W. Spratford, "Lower Extremity Kinematics and Kinetics When Landing From Unloaded and Loaded Jumps," J Appl Biomech, vol. 28, no. 6, pp. 687–693, Dec. 2012, doi: 10.1123/jab.28.6.687.
36. A. G. Thompsen, T. Kackley, M. A. Palumbo, and A. D. Faigenbaum, "Acute Effects of Different Warm-Up Protocols with and without a Weighted Vest on Jumping Performance in Athletic Women," J Strength Cond Res, vol. 21, no. 1, pp. 52–56, Feb. 2007, doi: 10.1519/00124278-200702000-00010.
37. R. Khlifa et al., "Effects of a Plyometric Training Program With and Without Added Load on Jumping Ability in Basketball Players," J Strength Cond Res, vol. 24, no. 11, pp. 2955–2961, Nov. 2010, doi: 10.1519/JSC.0b013e3181e37fbe.
38. J. P. Lake, P. D. Mundy, P. Comfort, J. J. McMahon, T. J. Suchomel, and P. Carden, "The effect of barbell load on vertical jump landing force-time characteristics," J Strength Cond Res, p. 1, Feb. 2018, doi: 10.1519/JSC.0000000000002554.
39. G. K. Lenton, T. L. A. Doyle, D. G. Lloyd, J. Higgs, D. Billing, and D. J. Saxby, "Lower-limb joint work and power are modulated during load carriage based on load configuration and walking speed," J Biomech, vol. 83, pp. 174–180, Jan. 2019, doi: 10.1016/j.jbiomech.2018.11.036.
40. P. H. Sessoms et al., "Effect of a load distribution system on mobility and performance during simulated and field hiking while under load," Ergonomics, vol. 63, no. 2, pp. 133–144, Feb. 2020, doi: 10.1080/00140139.2019.1690710.
41. K. D. Dahl, H. Wang, J. K. Popp, and D. C. Dickin, "Load distribution and postural changes in young adults when wearing a traditional backpack versus the BackTpack," Gait Posture, vol. 45, pp. 90–96, Mar. 2016, doi: 10.1016/j.gaitpost.2016.01.012.
42. G. K. Lenton, D. J. Saxby, D. G. Lloyd, D. Billing, J. Higgs, and T. L. A. Doyle, "Primarily hip-borne load carriage does not alter biomechanical risk factors for overuse injuries in soldiers," J Sci Med Sport, vol. 22, no. 2, pp. 158–163, Feb. 2019, doi: 10.1016/j.jsams.2018.06.013.
43. S. A. Birrell and R. A. Haslam, "The effect of load distribution within military load carriage systems on the kinetics of human gait," Appl Ergon, vol. 41, no. 4, pp. 585–590, Jul. 2010, doi: 10.1016/j.apergo.2009.12.004.
44. B. X. W. Liew, N. E. Helwig, S. Morris, and K. Netto, "Influence of proximal trunk borne load on lower limb countermovement joint dynamics," J Biomech, vol. 79, pp. 223–226, Oct. 2018, doi: 10.1016/j.jbiomech.2018.08.009.
45. A. C. Fain, K. D. Seymore, N. J. Lobb, and T. N. Brown, "Lower-Limb Biomechanics Differ Between Sexes During Maximal Loaded Countermovement Jumps," J Strength Cond Res, vol. 35, no. 2, pp. 325–331, Feb. 2021, doi: 10.1519/JSC.0000000000003889.
46. A. Kulas, P. Zalewski, T. Hortobagyi, and P. DeVita, "Effects of added trunk load and corresponding trunk position adaptations on lower extremity biomechanics during drop-landings," J Biomech, vol. 41, no. 1, pp. 180–185, Jan. 2008, doi: 10.1016/j.jbiomech.2007.06.027.
47. A. S. Donskov, J. S. Brooks, and J. P. Dickey, "Reliability of the Single-Leg, Medial Countermovement Jump in Youth Ice Hockey Players," Sports, vol. 9, no. 5, p. 64,

May 2021, doi: 10.3390/sports9050064.
48. G. Laffaye, P. P. Wagner, and T. I. L. Tombleson, "Countermovement Jump Height: Gender and Sport-Specific Differences in the Force-Time Variables," J Strength Cond Res, vol. 28, no. 4, pp. 1096–1105, Apr. 2014, doi: 10.1519/JSC.0b013e3182a1db03.
49. J. R. Harry, C. R. James, and J. S. Dufek, "Weighted vest effects on impact forces and joint work during vertical jump landings in men and women," Hum Mov Sci, vol. 63, pp. 156–163, Feb. 2019, doi: 10.1016/j.humov.2018.12.001.
50. J. S. Dufek and B. T. Bates, "The evaluation and prediction of impact forces during landings," Med Sci Sports Exerc, vol. 22, no. 3, p. 370???377, Jun. 1990, doi: 10.1249/00005768-199006000-00014.
51. F. C. Anderson and M. G. Pandy, "A Dynamic Optimization Solution for Vertical Jumping in Three Dimensions," Comput Methods Biomech Biomed Engin, vol. 2, no. 3, pp. 201–231, Jan. 1999, doi: 10.1080/10255849908907988.
52. F. C. Anderson and M. G. Pandy, "Dynamic Optimization of Human Walking," J Biomech Eng, vol. 123, no. 5, pp. 381–390, Oct. 2001, doi: 10.1115/1.1392310.
53. S. L. Delp, J. P. Loan, M. G. Hoy, F. E. Zajac, E. L. Topp, and J. M. Rosen, "An interactive graphics-based model of the lower extremity to study orthopaedic surgical procedures," IEEE Trans Biomed Eng, vol. 37, no. 8, pp. 757–767, 1990, doi: 10.1109/10.102791.
54. G. T. Yamaguchi and F. E. Zajac, "A planar model of the knee joint to characterize the knee extensor mechanism," J Biomech, vol. 22, no. 1, pp. 1–10, Jan. 1989, doi: 10.1016/0021-9290(89)90179-6.
55. F. Faul, E. Erdfelder, A.-G. Lang, and A. Buchner, "G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences," Behav Res Methods, vol. 39, no. 2, pp. 175–191, May 2007, doi: 10.3758/BF03193146.
56. F. Faul, E. Erdfelder, A. Buchner, and A.-G. Lang, "Statistical power analyses using G*Power 3.1: Tests for correlation and regression analyses," Behav Res Methods, vol. 41, no. 4, pp. 1149–1160, Nov. 2009, doi: 10.3758/BRM.41.4.1149.
57. A. Seth et al., "OpenSim: Simulating musculoskeletal dynamics and neuromuscular control to study human and animal movement," PLoS Comput Biol, vol. 14, no. 7, p. e1006223, Jul. 2018, doi: 10.1371/journal.pcbi.1006223.
58. S. L. Delp et al., "OpenSim: Open-Source Software to Create and Analyze Dynamic Simulations of Movement," IEEE Trans Biomed Eng, vol. 54, no. 11, pp. 1940–1950, Nov. 2007, doi: 10.1109/TBME.2007.901024.
59. K. Kipp and H. Kim, "Relative contributions and capacities of lower extremity muscles to accelerate the body's center of mass during countermovement jumps," Comput Methods Biomech Biomed Engin, vol. 23, no. 12, pp. 914–921, Sep. 2020, doi: 10.1080/10255842.2020.1772764.
60. R. Ueno et al., "Quadriceps force and anterior tibial force occur obviously later than vertical ground reaction force: a simulation study," BMC Musculoskelet Disord, vol. 18, no. 1, p. 467, Dec. 2017, doi: 10.1186/s12891-017-1832-6.
61. J. R. Harry, J. F. Silvernail, J. A. Mercer, and J. S. Dufek, Bilateral comparison of vertical jump landings and step-off landings from equal heights, vol. 32, no. 7. 2018. doi: 10.1519/JSC.0000000000002093.
62. J. R. Harry, J. Freedman Silvernail, J. A. Mercer, and J. S. Dufek, "Comparison of pre-contact joint kinematics and vertical impulse between vertical jump landings and step-off landings from equal heights," Hum Mov Sci, vol. 56, no. August, pp. 88–97, 2017, doi: 10.1016/j.humov.2017.10.022.
63. T. N. Brown, M. O'Donovan, L. Hasselquist, B. Corner, and J. M. Schiffman, "Lower limb flexion posture relates to energy absorption during drop landings with soldier-relevant body borne loads," Appl Ergon, vol. 52, pp. 54–61, Jan. 2016, doi: 10.1016/j.apergo.2015.06.004.
64. J. R. Harry, L. A. Barker, J. D. Eggleston, and J. S. Dufek, "Evaluating Performance During Maximum Effort Vertical Jump Landings," J Appl Biomech, vol. 34, no. 5, pp. 403–409, Oct. 2018, doi: 10.1123/jab.2017-0172.
65. J. Baus, J. R. Harry, and J. Yang, "Effects of sex and weighted vest load arrangements on lower biomechanics and jump height during countermovement jump," in Proceedings of the 7th International Digital Human Modeling Symposium (DHM 2022) and Iowa Virtual Human Summit 2022 -, Aug. 2022. doi: 10.17077/dhm.31763.
66. G. M. Sullivan and R. Feinn, "Using Effect Size—or Why the P Value Is Not Enough," J Grad Med Educ, vol. 4, no. 3, pp. 279–282, Sep. 2012, doi: 10.4300/JGME-D-12-00156.1.
67. S. S. Sawilowsky, "New Effect Size Rules of Thumb," Journal of Modern Applied Statistical Methods, vol. 8, no. 2, pp. 597–599, Nov. 2009, doi: 10.22237/jmasm/1257035100.
68. T. J. Suchomel, C. B. Taber, and G. A. Wright, "Jump Shrug Height and Landing Forces Across Various Loads," Int J Sports Physiol Perform, vol. 11, no. 1, pp. 61–65, Jan. 2016, doi: 10.1123/ijspp.2015-0028.
69. J. T. Kaplan et al., "Association Between Knee Anatomic Metrics and Biomechanics for Male Soldiers Landing With Load," Am J Sports Med, vol. 48, no. 6, pp. 1389–1397, May 2020, doi: 10.1177/0363546520911608.
70. K. D. Seymore, A. C. Fain, N. J. Lobb, and T. N. Brown, "Sex and limb impact biomechanics associated with risk of injury during drop landing with body borne load," PLoS One, vol. 14, no. 2, p. e0211129, Feb. 2019, doi: 10.1371/journal.pone.0211129.
71. C. E. Quatman, K. R. Ford, G. D. Myer, and T. E. Hewett, "Maturation leads to gender differences in landing force and vertical jump performance: A longitudinal study," American Journal of Sports Medicine, vol. 34, no. 5, pp. 806–813, 2006, doi: 10.1177/0363546505281916.

72. J. T. Weinhandl, M. Joshi, and K. M. O'Connor, "Gender Comparisons between Unilateral and Bilateral Landings," J Appl Biomech, vol. 26, no. 4, pp. 444–453, Nov. 2010, doi: 10.1123/jab.26.4.444.
73. T. E. Hewett et al., "Biomechanical Measures of Neuromuscular Control and Valgus Loading of the Knee Predict Anterior Cruciate Ligament Injury Risk in Female Athletes: A Prospective Study," Am J Sports Med, vol. 33, no. 4, pp. 492–501, Apr. 2005, doi: 10.1177/0363546504269591.
74. C. R. James, B. T. Bates, and J. S. Dufek, "Classification and Comparison of Biomechanical Response Strategies for Accommodating Landing Impact," J Appl Biomech, vol. 19, no. 2, pp. 106–118, May 2003, doi: 10.1123/jab.19.2.106.
75. C. R. James, L. T. Atkins, J. S. Dufek, and B. T. Bates, "An exploration of load accommodation strategies during walking with extremity-carried weights," Hum Mov Sci, vol. 35, pp. 17–29, Jun. 2014, doi: 10.1016/j.humov.2014.03.012.
76. J. L. Nuzzo, J. M. McBride, P. Cormie, and G. O. McCaulley, "Relationship Between Countermovement Jump Performance and Multijoint Isometric and Dynamic Tests of Strength," J Strength Cond Res, vol. 22, no. 3, pp. 699–707, May 2008, doi: 10.1519/JSC.0b013e31816d5eda.
77. N. E. Fowler, A. Lees, and T. Reilly, "Spinal shrinkage in unloaded and loaded drop-jumping," Ergonomics, vol. 37, no. 1, pp. 133–139, Jan. 1994, doi: 10.1080/00140139408963631.
78. N. E. Fowler, A. Lees, and T. Reilly, "Changes in stature following plyometric drop-jump and pendulum exercises," Ergonomics, vol. 40, no. 12, pp. 1279–1286, Dec. 1997, doi: 10.1080/001401397187360.
79. J. R. Harry, L. A. Barker, and M. R. Paquette, A Joint Power Approach to Define Countermovement Jump Phases Using Force Platforms, vol. 52, no. 4. 2020. doi: 10.1249/MSS.0000000000002197.
80. A. Lees, J. Vanrenterghem, and D. De Clercq, "Understanding how an arm swing enhances performance in the vertical jump," J Biomech, vol. 37, no. 12, pp. 1929–1940, 2004, doi: 10.1016/j.jbiomech.2004.02.021.
81. J. G. Claudino et al., "The countermovement jump to monitor neuromuscular status: A meta-analysis," J Sci Med Sport, vol. 20, no. 4, pp. 397–402, Apr. 2017, doi: 10.1016/j.jsams.2016.08.011.
82. M. Terada and P. A. Gribble, "Jump landing biomechanics during a laboratory recorded recurrent ankle sprain," Foot Ankle Int, vol. 36, no. 7, pp. 842–848, 2015, doi: 10.1177/1071100715576517.
83. W. Niu, Y. Wang, Y. He, Y. Fan, and Q. Zhao, "Kinematics, kinetics, and electromyogram of ankle during drop landing: A comparison between dominant and non-dominant limb," Hum Mov Sci, vol. 30, no. 3, pp. 614–623, 2011, doi: 10.1016/j.humov.2010.10.010.
84. Y. Morishige et al., "Difference in leg asymmetry between female collegiate athletes and recreational athletes during drop vertical jump," J Orthop Surg Res, vol. 14, no. 1, p. 424, Dec. 2019, doi: 10.1186/s13018-019-1490-5.