Effects of sex and weighted vest load arrangements on lower biomechanics and jump height during countermovement jump

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Abstract

Weighted vest (WV) use has been explored as a modifier of jumping and landing performance in athletes, but it is unclear whether performance is modified with different WV loading arrangements. The purposes of this study were to a) examine the effects of different external load arrangements on vertical jump height and lower-extremity biomechanics during a countermovement jump and b) understand the effects on men versus women. A scaled musculoskeletal gait model in OpenSim was used with sagittal plane inverse kinematics procedures for 24 participants (75.71 ± 18.88 Kg; 1.71 ± 0.09 m) equally divided between men and women performing jump-landing in four weighted vest loading conditions (back-loaded, front-loaded, split-loaded, unloaded). Mixed-model factorial analyses of variance (α=0.05) and effect sizes (ES) were used to identify and quantify differences between sexes and loading conditions. Regardless of loading conditions, men showed greater jump height (p<0.001, ES=2.22) and greater hip (p<0.001, ES=1.59), and knee (p=0.026, ES=0.90) moments. No significant difference in the hip (p=0.478, ES=0.30) or knee (p=0.580, ES=0.23) angular displacement was observed between men and women. Without considering sex, the unloaded condition showed greater jump height (p<0.001, ES=0.4), hip displacement (p=0.006, ES=0.34), and hip (p=0.019, ES=0.36), and knee (p=0.004, ES=0.48) moments when compared to the back-loaded condition. Jump height (p=0.04, ES=0.1) and hip moments (p=0.028, ES=0.36) were also greater for the split-loaded compared to the back-loaded condition. Both the unloaded and split-loaded conditions showed greater jump height (p<0.001, ES=0.4; p<0.001, ES=0.3) and hip moments (p<0.001, ES=0.55; p=0.003, ES=0.35) compared with the front-loaded condition. A significantly greater magnitude of the hip displacement was detected for the split loaded condition compared to the front-loaded condition (p<0.001, ES=0.19). These results indicate that different external loading arrangements significantly affect the biomechanical performance output and differences in the load accommodation strategies between men and women during the period between the weighting and propulsion phases of jumping.

Keywords: Countermovement jump, biomechanics, weighted vest, jump height

Introduction

Countermovement jump is a common practice in professional sports that, at the same time, is used to evaluate jumping performance and joint biomechanics. The countermovement jump consists of the subject standing, followed by a downward movement and a rapid upward movement to cause take-off [1]. Jumping performance studies seek opportunities to improve jumping techniques. At the same time, they analyze joint kinetics and kinematics to identify biomechanical performance of postural adjustment and center of mass shifting to maintain balance [2]. Jumping performance is closely related to the jumping technique that can be improved through different strategies [3]–[6]. It is essential to mention that an increased jump height will also increase the landing height, which requires a greater mechanical demand during the landing phase on the hip, knee, and ankle joints[7].

A weighted vest is one of many possible practices to add an external load to improve jumping performance in training. It is recommended to use an extra 10-15% body weight (BW) as the external load for training practices to enhance vertical jump height [8]–[10]. A warming-up protocol with a 2%

BW weighted vest effectively enhanced jumping performance [11]. Typically, the load on the weighted vest is positioned such that it is symmetrically arranged over the trunk. Asymmetrically loading the weighted vest can also cause different biomechanical demands during jumping and landing [12]. Modified hip, knee, and ankle responses have been observed for symmetrical loading, causing different energy absorption during the landing phase [13]. External loading studies are commonly done for the landing phase because during this period, the jumper experiences the peak ground reaction forces, so the injury risk is increased [14], [15].

In contrast, this study focuses on the jumping's weighting, unweighting, breaking, and flying phases that define the jumping performance [16]. The purpose of this study is to investigate the knee and hip kinetics and kinematics for different load arrangements of weighted vests. We hypothesize that the jump height will be greater in magnitude in men than women and for the unloaded case compared to the other loading conditions. Also, it is expected to observe lower hip and knee moment and angular displacement for women and the unloaded condition. The novelty of this study is that four different loading arrangements (back-loaded, front-loaded, split-loaded, and unloaded) are tested for hip and knee kinetic sand kinematics comparison using OpenSim software [17], [18]. We expect to find significant differences when comparing the unloaded condition with any other loading conditions. Also, we hope to see significant differences when comparing the split-loaded condition against the front-loaded and back-loaded conditions.

Methods

Participants

Twenty-four recreationally active adults (26.13 ± 3.33 years) were recruited for this study and among them there were 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). The recruit criterion was that they did not have a recent history (≤ 1 year) of significant injuries in the lower extremities. Institutional Review Board approved the experimental protocol at the site of data collection.

Experimental Protocol

Data collection was conducted in a single laboratory session that started with collecting demographic and anthropometrics of each participant (gender, age, mass, height). Participants were provided with appropriate-sized athletic shoes (Vazee Pace v2; New Balance Athletics, Inc., Boston, MA) as a control method for potential footwear effects. After the protocol was explained, the participants went through a standardized warm-up protocol that required five-minute walking or jogging on a treadmill at a self-selected pace and five vertical jump landings (VJL) separated by 30 seconds. Posteriorly, the participants performed eight maximum effort countermovement jumps in four experimental conditions. The conditions were defined as 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) by wearing a weighted vest (Mir Vest, Inc., San Jose, CA, USA). The loading conditions were presented to the participants in a counterbalanced order.

The participants were instructed to start the trial by positioning each foot on a force platform and later perform the jump using a self-selected countermovement depth and preferred arm swing strategy. It was required to be considered a fair trial for the participant to land with each foot in contact with a force platform and return to a motionless standing position. A trial was discarded if the jump appeared to be submaximal effort, the participant could not land with each foot in an individual force platform, or the participant could not return to the motionless standing position.

Three-dimensional kinematic data were obtained using a 10-camera motion capture system (Vicon Motion Systems, Ltd., Oxford, UK; 200 Hz) that tracked reflective spherical markers (14mm). The markers were positioned in 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. Also, three-marker cluster sets adhered bilaterally over the calcaneus. Four-marker cluster sets adhered bilaterally to the lateral aspect of the thigh and shank to complete the set. Simultaneously, a dual force platform system (Kistler Instruments, Corp., Amherst, NY; 1000 Hz) was used to obtain three-dimensional ground reaction force (GRF) data.

Data Processing

Subject-specific musculoskeletal models were scaled using OpenSim [17], [18] software from a gait model that has no upper extremities (Gait 2354) [19]–[22]. The scaling process required adjusting the generic model with the height and weight of each participant and inputting estimated values of the inertial properties. Once the model was scaled to a specific participant, an inverse kinematic (IK) analysis was done by reducing the error between the position of the physical markers data obtained with motion capture with the virtual markers on the model [23]. The obtained results provide the joint kinematics necessary to perform the inverse dynamics (ID) process to give the internal joint moments.

After the results from ID were smoothed with a Butterworth filter with a cut-off frequency of 6Hz, the results were exported to MATLAB® to divide the jumping motion into propulsion and flying phases based on the ground reaction force data. The propulsion phase was defined from the onset movement to the take-off instant. The flying phase was defined from take-off to ground contact [16]. The maximum joint displacement and moment were taken from the right limb since asymmetries in the sagittal plane are unlikely to happen [24]–[26]. Taking advantage of the OpenSim analysis tool, the body center of mass position was calculated to obtain the maximum jump height during the flying phase as the difference between the highest position of the center of mass position during the flying phase and at the beginning motionless standing position.

Statistical Analysis

The mean and standard deviation (SD) of kinetic and kinematic values were calculated for each participant's trial for each loading condition. IBM SPSS software (v28; IBM Corp., Armonk, NY) was used to run a mixed-model factorial ANOVA (α=0.05), with sex as the between factor and loading condition as the within factor. In the case of a significant interaction, independent sample t-test and paired sample t-test were used to assess sex differences between loading conditions and loading conditions differences between sex, respectively. When no significant interaction was detected, Sidak adjustment was used to compare the main effects. The data normality was assessed using the Shapiro-Wilk test. Cohen's d effect sizes (ES) were calculated to normalize the magnitude of the mean differences and identify the presence of a meaningful effect [27]. Sawilowsky's scale was selected to interpret the values of the effects size. The scale is defined as follow: very small: $ES<0.2$, small: $0.2\leq ES<0.5$, medium: $0.5\leq ES<0.8$, large: $0.8\leq ES<1.2$, very large: $1.2\leq ES<2.0$, and huge: $ES\geq 2.0$ [28].

Results

The data presented the flexion and flexion moment in thi section is defined as positive for both the knee and hip joints. Hip and knee moments were normalized with respect to system weight (subject and weighted vest mass). No significant interactions were detected for the maximum jump height (p=0.579), hip (p=0.499) and knee (p=0.269) moment, or hip (p=0.541) or knee (p=0.851) angular displacement. Accordingly, main effects were obtained for the differences between sexes with pooled load conditions and load conditions with pooled sex data.

Sex effects

Statistical analysis results for the sex data are listed in Table 1. A huge sex difference was detected for greater maximum jump height (p<0.001, ES=2.22) for men compared to women. A very large difference was detected for the hip moment (p<0.001, ES=1.59), with a greater magnitude for men than women. For the knee moment, a large difference was detected (p=0.026, ES=0.90) with greater magnitude in the case of men compared to women. No significant differences were detected for hip (p=0.478, ES=0.30) and knee (p=0.580, ES=0.23) angular displacement.

Table 1:Differences between Men and Women

Variables	Men		Women			
	Mean	SD	Mean	SD	p	ES
Jump Height*	0.49	0.08	0.34	0.06	<0.001	2.22
Hip Displacement	91.30	19.66	86.34	13.89	0.478	0.30
Hip Moment*	2.09	0.40	1.51	0.36	<0.001	1.59
Knee Displacement	107.21	12.75	104.82	8.73	0.580	0.23
Knee Moment*	1.69	0.22	1.52	0.17	0.026	0.90

Note: Units of measurement for jump height (m), hip and knee displacement (°), hip and knee moment ($N\ m\ Kg^{-1}$); 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).

Load condition effects

Results for load condition data are presented in Table 2. For the jump height, small load condition differences were detected with greater jump height for the unloaded condition when compared to the back-loaded condition (p<0.001, ES=0.4), the front-loaded condition (p<0.001, ES=0.4), and split-loaded condition (p<0.001, ES=0.3). Also, a very small difference was detected for a more significant jump height when comparing the back-loaded and split-loaded conditions (p=0.04, ES=0.1). Small significant differences were seen for the hip moment with a smaller magnitude for the back-loaded condition when compared to the split-loaded condition (p=0.028, ES=0.36) and with the unloaded condition (p=0.019, ES=0.36). For the knee moment, a small significant difference was detected with greater magnitude for the unloaded condition compared to the back-loaded condition (p=0.004, ES=0.48). Small significant differences were seen for the hip angular displacement with greater magnitude for the unloaded condition when compared to the back-loaded (p=0.006, ES=0.34) and split-loaded (p=0.003, ES=0.35) conditions. A medium significant difference was detected with greater hip angular displacement for the unloaded condition than the front-loaded condition (p<0.001, ES=0.55). A greater magnitude of hip angular displacement for the split-loaded condition than the front-loaded condition showed a very small significant difference (p<0.001, ES=0.19).

Table 2: Differences between Loading Conditions

Variables	Back-loaded		Front-loaded		Split-loaded		Unloaded		
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	p
Jump Height †‡§¶	0.40	0.10	0.40	0.10	0.41	0.10	0.44	0.11	<0.001
Hip Displacement †§¶#	88.36	16.69	84.92	17.23	88.14	17.67	93.85	16.71	<0.001
Hip Moment †‡	1.70	0.48	1.78	0.50	1.87	0.50	1.86	0.44	<0.001
Knee Displacement	105.44	9.91	105.46	9.90	106.88	11.99	106.27	12.34	0.498
Knee Moment †	1.55	0.23	1.60	0.19	1.60	0.18	1.66	0.25	0.015

Note: Units of measurement for jump height (m), hip and knee displacement (°), hip and knee moment ($N\ m\ Kg^{-1}$); 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 back-loaded and split-loaded conditions ($p<0.05$), § significant difference between front-loaded and unloaded conditions ($p<0.05$), ¶ significant difference between split-loaded and unloaded conditions ($p<0.05$), # significant difference between front-loaded and split-loaded conditions ($p<0.05$).

Discussion

This study aimed to investigate if using different loading arrangements as a weighted vest during the first phases of countermovement jump will alter the jump height and biomechanics of the hip and knee joints in male and female subjects. From the first hypothesis, for pooled loading conditions (Table 1), a higher jumping height was observed for men than women, which is consistent with results previously reported in the literature [29]. When looking at Table 2, the unloaded condition showed the highest jump height since it has a lesser mechanical demand than other loading conditions, so there is less mass to overcome. The significant differences in the jump height and hip moment between the back-loaded and the split-loaded conditions suggest that the load arrangement does influence the performance output with a more substantial jump height with less hip involvement. Previous studies have investigated the progressive use of loading strategies over different periods, showing improvements in jump height [30], [31]. Our study did not focus on warm-up or training protocols to obtain better jumping performance results in the long term, so a future study could implement the different load and different loading arrangements, as proposed in this paper, to investigate the improvement in jump height [32], [33].

By looking at Table 1, there is a significant difference between male and female subjects for both knee and hip moments. Considering that men are typically stronger from a gross perspective, they can sustain much higher stretch loads [34]; it is shown that they also generate more relative torque during jumping. These results are consistent with previous studies reporting that higher jumps are directly related to more significant knee and hip moments [35]. Muscle strength and power output have been considered predictors of jumping performance [30]. Still, we are looking at a situation where joint moments could be viewed as another critical factor in this prediction. In the case of joint angular displacement, a significant difference was found only for the hip joint, comparing different loading conditions (Table 2). Previous studies have reported trunk position adaptations with the added external load during landing [13] and differences in the hip work between men and women with different energy storage or concentric mechanical output [36]. Our results suggest that there might be similar adaptations during the unweighting, breaking, and propulsion phases of jumping. Even when the results followed our hypothesis, the small differences in jump height and hip moment need further investigation to find their meaningfulness in this context.

The differences in kinetic and kinematic factors could be considered an accommodation strategy [37] that differs between men and women and across loading conditions in response to a change in an external stressor in the form of additional external weight to the body. It is essential to mention that, even when similar jump height could be achieved for different jumpers, its downward phase movement strategy during the countermovement jump could be different. During the unweighting and breaking phases of jumping, the joints' kinetic and kinematics qualities may differ from one subject to another, so differences in joints' moment and angular displacement are expected [38]. Also, short-term and long-term responses are different because neuromuscular and metabolic adaptations have been observed for external loading conditions [39]. Finally, it is worth mentioning that all results were kinetic and kinematic results were obtained using OpenSim. A future study could test the reliability of these results when comparing with other software with the same capabilities in simulation and predicting biomechanical parameters.

Conclusion

This study showed adjustment in the knee and hip moments for the back-loading condition as a strategy to achieve greater jump height during the flying phase of the countermovement jump. Because of symmetrical and asymmetrical loading, there was a significant difference in the jump height and the hip moment when comparing the back-loaded and the split-loaded conditions. The same behavior was observed for the hip angular displacement in comparing front-loaded and split-loaded conditions. In contrast, independent of the symmetry or asymmetry of the additional load, significant differences were detected for jump height and hip displacement for the front-loaded versus unloaded and the split-loaded versus unloaded cases. When comparing sex, large, very large, and huge effects sizes were detected for knee moment, hip moment, and jump height, respectively, suggesting that differences are meaningful. Different loading arrangements may be implemented in various warm-up protocols or training programs depending on the implementation of and desired results in terms of performance.

Acknowledgments

This work was supported by Distinguished Graduate Student Fellowship, Graduate School, Texas Tech University.

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