Weighted vest effects on impact forces and joint work during vertical jump landings in men and women

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ABSTRACT

Weighted vest (WV) use during vertical jump landings (VJL) does not appear to alter peak vertical ground reaction forces (GRF) or peak joint torques. However, WV effects on joint work and sex differences during VJL are not well understood. This study assessed WV effects on vertical GRF and sagittal joint work during VJL in men and women. Twelve men and 12 women performed VJL wearing a WV with zero added mass (unloaded) and with 10% body mass (loaded) while GRF and kinematic data were obtained. Mixed-model analyses of variance ($\alpha = 0.05$) and effect sizes (ES) were used to assess differences between sexes and/or load conditions. Regardless of sex, greater landing height ($p < 0.001$; ES = 0.37) and peak vertical GRF ($p = 0.001$; ES 0.51) occurred when unloaded, while greater landing time ($p = 0.001$; ES = 0.46) and negative lower extremity work ($p < 0.001$; ES = 0.41) occurred when loaded through greater negative work about the hip ($p = 0.001$; ES = 0.27) and ankle ($p = 0.020$; ES = 0.27). No differences in hip ($p = 0.753$; ES = 0.03), knee ($p = 0.588$; ES = 0.07), or ankle ($p = 0.580$; ES = 0.09) joint displacement were detected between loaded and unloaded conditions. Men exhibited greater landing heights ($p < 0.001$; ES = 2.49) and greater peak vertical GRF than women ($p = 0.007$; ES = 1.18), though women exhibited greater negative lower extremity work ($p < 0.001$; ES = 1.98) than men through greater negative knee ($p < 0.001$; ES = 1.98) and ankle ($p = 0.032$; ES = 0.94) work. No sex differences were detected for joint angular displacement about the hip ($p = 0.475$; ES = 0.30), knee ($p = 0.666$; ES = 0.18), or ankle ($p = 0.084$; ES = 0.71). These data revealed a unique load accommodation strategy during VJL with a WV characterized by greater lower extremity joint work performed via increased joint torque despite lesser landing height and peak vertical GRF. Women appear to perform greater lower extremity joint work than men during VJL despite lesser landing height and peak vertical GRF. Current and prospective WV users should be aware of their load accommodation strategy during VJL with an external load. Women may consider developing more refined load accommodation strategies for VJL regardless of whether external loading is applied to avoid performing excessive amounts of lower extremity work.

1. Introduction

It is well documented that external loading via weighted vest (WV) use (~10–13% added body mass) during both acute and

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chronic physical training can improve vertical jump performance (Bosco et al., 1984; Khlifa et al., 2010; Thompsen, Kackley, Palumbo, & Faigenbaum, 2007). However, the vertical jump requires the subsequent execution of a landing (i.e., vertical jump landing; VJL) during which rapid attenuation of large vertical ground reaction forces (GRF) occurs (Harry, Barker, Mercer, & Dufek, 2017). The vertical GRF relates to the amount of mechanical energy in the system, and the negative angular work performed about the lower extremity joints represents the amount of energy absorbed to attenuate vertical GRF and terminate downward center of mass (COM) motion (Norcross et al., 2013). Increased joint work during landing from consistent heights (i.e., step-off style drop landings) without a WV or other means for external loading has been linked to both decreased vertical GRF magnitudes (Devita & Skelly, 1992; Zhang, Bates, & Dufek, 2000) and decreased forces experienced by the passive structures within the lower extremity joints (Yeow, Lee, & Goh, 2011). However, a WV increases the biomechanical demands placed on the user via increased inertia and thus an increased magnitude of mechanical energy in the system. As such, it is important to consider how WV use can alter vertical GRF and joint work during landing since an increase in joint work does not always coincide with a lesser peak vertical GRF and passive tissue loading. For instance, WV use (~10% body mass) during step-off landings from a 45 cm platform increased both knee and ankle joint work by 12% and 9%, respectively, among recreationally active men and women (Kulas, Zalewski, Hortobagyi, & DeVita, 2008). The greater joint work values were the result of increased biomechanical demands related to a greater amount of mechanical energy accumulated by the time of ground contact (Kulas et al., 2008), which likely coincides with increased peak vertical GRF magnitudes as a result of increased system mass (Nordin, Dufek, James, & Bates, 2017; Sell et al., 2010).

During VJL with and without a WV, jump-landing height should decrease when loaded because of greater biomechanical demands placed on the user during the jump phase. For example, jump-landing height was shown to decrease by approximately 11% during VJL with a WV (~10% body mass) when compared to VJL with no WV in trained male volleyball players because of greater inertia (Janssen, Sheppard, Dingley, Chapman, & Spratford, 2012). Due to the decrease in jump-landing height, peak vertical GRF, peak joint torque, leg stiffness, and joint displacement did not differ between load conditions despite greater system mass (Janssen et al., 2012). When even greater external loads (25%, 50%, 75%, and 100% body mass delivered via loaded barbells) were accommodated during VJL, average vertical GRF magnitudes decreased with heavier loads among strength-trained men due to decreased jump-landing heights (Lake, Mundy, Comfort, McMahon, Suchomel, & Carden, 2018). Similarly, when external loading was increased during trials of the "jump-shrug" exercise (30%, 45%, 65%, 80% of 1RM hang power clean) in a mixed sample of track and field and recreational athletes, the peak vertical GRF magnitude during landing decreased with each load increase because of a decreased jump height (Suchomel, Taber, & Wright, 2016). The evidence reviewed indicates differences in jump-landing height should be considered when assessing the effects of WV use during landings (Janssen et al., 2012; Lake, et al., 2018; Suchomel et al., 2016), since the decrease in jump-landing height may "outweigh" the increased system mass with respect to impact characteristics. Despite previous assessments of vertical GRF parameters during VJL with and without a WV, no study to date has determined whether joint work is altered during VJL in response to WV use.

In addition to the lack of available evidence regarding joint work changes during VJL with a WV, no study to date has determined whether men and women respond similarly to WV use during VJL. This is especially important because women and men have been shown to perform similar angular work about the knee during step-off landings from heights equal to maximum vertical jump height even though women performed more work about the ankle (Weinhandl, Irmischer, & Sievert, 2015). This distally-dominant energy absorption strategy displayed by women is thought to increase the forces experienced by passive structures within the knee (Norcross, Blackburn, Goerger, & Padua, 2010; Weinhandl et al., 2015). What remains unknown is whether similar energy absorption differences occur between men and women during VJL with a WV, where normal environmental demands are increased. However, a recent study comparing a less invasive environmental change from standard to minimal footwear during jumping observed different joint work responses in women versus men (Smith, Paquette, Harry, Powell, & Weiss, 2018). Thus, it a reasonable to presume a sex-specific response may occur when wearing a WV during VJL compared to when not wearing a WV. Still, sex-specific responses to WV use during VJL remain unexplored.

The purpose of this investigation was to assess the effects of WV use on vertical GRF and joint work during VJL in men and women. The following hypotheses were tested: 1) WV use would not alter peak vertical GRF and joint work characteristics in men and women due to a corresponding decrease in jump-landing height, and 2) lesser vertical GRF but increased joint work would be exhibited by women in comparison to men during VJL with and without a WV.

2. Methods

2.1. Participants

Twenty-four adults consisting of 12 men (88.8 ± 16.4 kg; 1.8 ± 0.1 m; 27 ± 3 y) and 12 women (62.7 ± 10.3 kg; 1.7 ± 0.1 m; 25 ± 3 y) participated in this study. This sample was determined via an *a priori* power analysis using G*Power v3.1 software (Faul, Erdfelder, Lang, & Buchner, 2009) and published ankle work data from men and women during landings from a height equal to maximum jump height (Weinhandl et al., 2015). Based on a proposed effect size of 1.0, power (1-β) of 0.80, and an alpha (α) of 0.05, the current sample of 24 participants (n = 12 per group) provided adequate statistical power. Participants were defined as recreationally active due to their engagement in activities involving jump-landings for at least six months prior to the study. All were free of any condition or ailment that would have limited their ability to perform maximum effort VJL. Written informed consent was obtained from all participants as approved by the Institutional Review Board at the site of data collection.

2.2. Procedures

Participants completed all tests during one visit to the laboratory. Age, sex, height, and mass were recorded, and participants were shown a demonstration of the protocol and provided with standard laboratory footwear (Vazee Pace v2; New Balance Athletics, Inc., Boston, MA). Participants completed a standardized warm-up consisting of five minutes of walking and/or jogging on a treadmill at a self-selected pace followed by five VJLs separated by approximately 30 s with intensity progressing from moderate to maximum effort. Spherical (14 mm) reflective markers were adhered bilaterally to the following locations using hypoallergenic tape: iliac crest, anterior superior iliac spine, posterior superior iliac spine, medial and lateral aspects of the knee, medial and lateral malleoli, and the distal aspect of the second metatarsal. A single reflective marker was adhered over the sacrum. Plastic shells with four non-collinear reflective markers were adhered to the lateral aspect of the thigh and leg segments using neoprene wraps and hypoallergenic adhesive tape, while three non-collinear markers were adhered over the heel counter of the shoes. Three-dimensional kinematic and GRF data were obtained synchronously using a 10-camera motion capture system (Vicon Motion Systems, Ltd., Oxford, UK; 200 Hz) and two force platforms (Kistler Instruments, Corp., Amherst, NY; 1000 Hz).

Following a static calibration trial, the reflective markers adhered to the iliac crests, anterior superior iliac spines, medial and lateral aspects of the knee and malleoli, and the metatarsals were removed while the remaining markers were retained for motion tracking. Then, participants completed eight VJL trials while wearing a vest (MiR Vest, Inc., San Jose, CA) with both no added mass (unloaded) and with 10% body mass (to the nearest 0.25 kg; loaded) distributed evenly over the anterior and posterior aspects of the trunk. All unloaded trials were performed before the loaded trials to ensure that the unloaded condition was not influenced by the loaded condition. Each VJL trial began with participants standing motionless with their arms hanging by their side and each foot positioned on a force platform. Participants initiated the VJL by performing a countermovement action, using a self-selected depth and arm swing to avoid compromised performance linked to constrained movements (Lees, Vanrenterghem, & De Clercq, 2004; Mosier, Fry, & Lane, 2017), before jumping as high as possible. Participants completed the VJL by landing with each foot contacting a force platform, terminating downward motion, and returning to a motionless standing position.

2.3. Data processing and analysis

Raw data were exported to the Visual 3D Biomechanical Software Suite (version 6; C-Motion, Inc., Germantown, MD). A four-segment model was constructed from the marker trajectories of the calibration trial to include the pelvis, thigh, leg, and foot segments. Marker trajectories and GRF data were smoothed using a low pass Butterworth digital filter with cutoff frequencies of 12 Hz and 50 Hz, respectively. The GRF data from the two force platforms were summed along the vertical axis to create a vertical GRF profile representative of the system COM. Landing height was calculated as the difference between the vertical positions of the pelvis COM at the apex of flight and ground contact (vertical GRF > 20 N after takeoff). The landing phase was defined as the time between ground contact and the end of downward pelvis COM motion (i.e., minimum pelvis COM position after ground contact). The vertical GRF data was then normalized to system mass (body mass + WV mass; $N*kg^{-1}$) and the peak vertical GRF was extracted from the vertical GRF versus time profile. If two vertical GRF peaks (i.e., passive peak and active peak) were present, the second peak magnitude was extracted because it is related to jump-landing height (Dufek & Bates, 1990; McNitt-Gray, 1991; Zhang et al., 2000).

A Cardan sequence (X-Y-Z) was used for hip, knee, and ankle joint angular calculations where X represents the medial–lateral axis, Y represents the anterior-posterior axis, and Z represents the longitudinal axis. Joint angles were expressed in degrees such that positive values represented a flexed/dorsiflexed position. Joint angular displacements were calculated as the change in joint angular position during the landing phase. Joint angular velocities at the hip, knee, and ankle were calculated as the time derivative of the joint angular positions. Sagittal net joint moments were computed at the hip, knee, and ankle using Newtonian inverse dynamics, and sagittal joint angular powers were calculated as the dot product of the sagittal net joint moments and joint angular velocities. The joint angular power curves during the landing phase were integrated with respect to time to determine the magnitude of net joint work (i.e., energy absorption) performed about the joints in the sagittal plane. The joint work values were normalized to system mass multiplied by landing height since the total magnitude of mechanical energy is proportional to landing height (Weinhandl et al., 2015; Weinhandl, Joshi, & O'Connor, 2010). Only the right limb was used for joint kinetic analyses since VJL were previously shown to not produce asymmetrical vertical GRF magnitudes or sagittal joint angular displacements (Harry, Freedman Silvernail, Mercer, & Dufek, 2017, 2018).

2.4. Statistical analyses

Mean values were calculated across trials per participant for each parameter. Mixed-model (sex by load) analyses of variance ($\alpha = 0.05$) were carried out in IBM SPSS Statistics software (v25; IBM Corp., Armonk, NY), with sex as the between factor and load condition as the within factor. If a significant interaction was detected, independent samples t-tests were carried out to compare differences between men and women for both the unloaded and loaded conditions, while dependent t-tests were carried out to compare differences between the loaded and unloaded conditions for both men and women. The Sidak adjustment was used for main effect comparisons if no significant interaction was detected. Data normality was assessed using the Shapiro-Wilk test. The *a priori* alpha level was adjusted to be more conservative (adjusted $\alpha = 0.025$) if normality was violated (Vincent & Weir, 2012). Because a significant p value indicates the presence of an effect and not the presence of a meaningful effect (Sullivan & Feinn, 2012), Cohen's *d* effect sizes (ES) were calculated to provide the normalized magnitude of the mean differences. The ES values were interpreted using Hopkins' (Hopkins, 2006) scale (e.g., trivial: < 0.20; small: 0.20–0.59; moderate: 0.60–1.19; large: 1.20–1.99; very large: ≥ 2.0).

Table 1

Differences between unloaded and loaded conditions and between men and women.

Variables	Load Condition Effects						Sex Effects					
	Unloaded		Loaded				Men		Women			
	Mean	SD	Mean	SD	p	ES	Mean	SD	Mean	SD	p	ES
Landing Height (m)*§	0.39	0.11	0.35	0.10	< 0.001	0.37	0.45	0.08	0.29	0.05	< 0.001	2.49
Landing Time (s)*	0.26	0.06	0.28	0.06	0.001	0.46	0.25	0.05	0.29	0.06	0.087	0.73
Peak Vertical GRF (N*kg^{-1})*§	42.24	11.35	37.12	9.23	0.001	0.51	44.83	11.39	34.53	6.01	0.007	1.18
Total LE Work (J/kg^{-1}/LH^{-1})*§	−5.52	1.44	−6.17	1.83	< 0.001	0.41	−4.72	0.90	−6.98	1.43	< 0.001	1.98
Hip Work (J/kg^{-1}/LH^{-1})*	−0.71	0.84	−0.97	1.10	0.001	0.27	−0.62	0.71	−1.05	1.18	0.281	0.46
Knee Work (J/kg^{-1}/LH^{-1})§	−3.58	0.91	−3.80	1.00	0.105	0.24	−3.03	0.70	−4.35	0.69	< 0.001	1.98
Ankle Work (J/kg^{-1}/LH^{-1})*§	−1.23	0.60	−1.40	0.62	0.020	0.27	−1.06	0.65	−1.57	0.47	0.032	0.94
Hip Displacement (°)	45.79	22.22	46.39	19.82	0.754	0.03	43.02	23.63	49.16	18.51	0.475	0.30
Knee Displacement (°)	63.94	11.67	64.72	9.82	0.588	0.07	63.41	11.71	65.26	10.16	0.666	0.18
Ankle Displacement (°)	46.21	12.23	47.34	13.59	0.580	0.09	42.56	14.47	50.99	9.96	0.084	0.71

Note: Mean = average across participants; SD = ± standard deviation; p = statistical probability; ES = Cohen's d effect size; Load condition effects = data for unloaded and loaded conditions with pooled sex data; Sex effects = data for men and women with pooled load condition data; LE = lower extremity; Total LE Work = summation of hip, knee, and ankle joint work values; Negative work values represent energy absorption.

  * = significant difference between unloaded and loaded conditions (p < 0.05).

  § = significant difference between men and women (p < 0.05).

3. Results

3.1. Interaction effects

A significant interaction was detected for hip joint work (p = 0.029). *Post hoc* analyses revealed a small difference in hip work in women, with a greater magnitude when loaded compared to when unloaded (−0.85 ± 1.01 J/kg^{-1}/LH^{-1}, unloaded; −1.26 ± 1.33 J/kg^{-1}/LH^{-1}, loaded; p = 0.004; ES = 0.37). No significant differences in hip work were detected between men and women during the unloaded (−0.57 ± 0.65 J/kg^{-1}/LH^{-1}, men; −0.85 ± 1.01 J/kg^{-1}/LH^{-1}, women; p = 0.430; ES = 0.34) or loaded (−0.68 ± 0.76 J/kg^{-1}/LH^{-1}, men; −1.26 ± 1.33 J/kg^{-1}/LH^{-1}, women; p = 0.198; ES = 0.32) conditions. No significant differences in hip work were detected between unloaded and loaded conditions in men (p = 0.141; ES = 0.16). No significant interactions were detected for any other variable (p > 0.05).

3.2. Sex effects

Sex data are presented in Table 1. A very large difference revealed greater landing heights in men than in women (p < 0.001; ES = 2.49). A moderate difference detected a greater peak vertical GRF in men versus women (p = 0.007; ES = 1.18). Large differences detected greater total lower extremity work (p < 0.001; ES = 1.98) and knee work (p < 0.001; ES = 1.98) in women versus men, while a moderate difference detected greater ankle work (p = 0.032; ES = 0.94) in women versus men. No significant differences between men and women were observed for landing time (p = 0.087; ES = 0.73) or joint displacement at the hip (p = 0.475; ES = 0.30), knee (p = 0.666; ES = 0.18), or ankle (p = 0.084; ES = 0.71).

3.3. Load condition effects

Load condition data are presented in Table 1. Small differences revealed greater landing heights (p < 0.001; ES = 0.37) and peak vertical GRF (p = 0.001; ES = 0.51) when unloaded versus loaded, while greater landing time (p = 0.001; ES = 0.46) occurred when loaded versus unloaded. Small differences revealed greater total lower extremity work (p < 0.001; ES = 0.41), hip work (p = 0.001; ES = 0.27), and ankle work (p = 0.020; ES = 0.27) when loaded versus when unloaded. No significant condition main effects were detected for knee work (p = 0.105; ES = 0.24) or angular displacement at the hip (p = 0.754; ES = 0.03), knee (p = 0.588; ES = 0.07), or ankle (p = 0.580; ES = 0.09) joints.

4. Discussion

The purpose of this investigation was to assess the effects of WV use on vertical GRF and joint work during VJL in men and women. Interaction effects revealed that women exhibited significantly greater hip joint work when loaded versus unloaded, though this difference was small in magnitude. Numerous small magnitude significant differences were detected between load conditions regardless of sex, with greater peak vertical GRF and greater landing height occurring when unloaded, while greater lower extremity joint work occurred when loaded through greater work about the hip and ankle joints. Numerous large magnitude significant differences were detected between men and women regardless of load condition, with men exhibiting greater peak vertical GRF and landing height, while women exhibited greater total lower extremity joint work than men through greater work about the knee and

ankle.

4.1. Load condition effects

Contrary to our first hypothesis, WV use during VJL was shown to alter peak vertical GRF, with a smaller magnitude occurring during the loaded condition. The smaller peak vertical GRF when loaded was surprising since it was previously shown that peak vertical GRF did not differ statistically between similar loaded and unloaded VJL, and the ES presented was trivial (Janssen et al., 2012). The difference in landing height between load conditions observed both here and in that study (Janssen et al., 2012) was approximately 11%, suggesting any vertical GRF differences between load conditions should also be similar between studies. However, the different peak vertical GRF results might be due to the current sample focusing more on decreasing impact forces (via increased landing time) while the sample of trained volleyball athletes evaluated previously (Janssen et al., 2012) might have been more focused on quickly terminating downward momentum to maintain specificity with their sport's demands. Other studies examining vertical GRF during other jump-landing maneuvers observed a similar decrease in peak vertical GRF during VJL-like maneuvers as system mass increased (via loaded barbells) because of lesser landing height (Lake, et al., 2018; Suchomel et al., 2016). With the current data included, only one study to date has observed an increased peak vertical GRF when increasing system mass during jump-landing movements (Dempsey, Handcock, & Rehrer, 2014), though that study added mass to the system via body armor and a police-issue equipment belt. Thus, it could be concluded that wearing a WV with 10% body mass (Janssen et al., 2012) or increasing system mass through other means (Lake, et al., 2018; Suchomel et al., 2016) is unlikely to increase injury potential relative to peak vertical GRF, such as stress fractures that can result from repetitive higher-magnitude external loading (McGee, Qureshi, & Porter, 2004). This result may be especially important when considering the current peak vertical GRF data with the system mass normalization removed, since a greater peak vertical GRF across participants, while not compared statistically, still occurred when unloaded (3198.2 ± 859.1 N) compared to loaded (3091.3 ± 768.7 N). While these vertical GRF results suggest decreased injury potential during WV use as it relates to stress fractures, the vertical GRF data should not be considered relative to muscle, tendon, or ligament injury potential.

Contrary to our first hypothesis, WV use during VJL was shown to alter joint work, with greater total lower extremity work (summation of hip, knee, and ankle joint work values) occurring when loaded versus unloaded through greater hip and ankle work. Our initial hypothesis was based on the lack of previously observed differences in peak joint torques and joint displacements between VJL with and without a loaded WV (Janssen et al., 2012) and the expectation that the involved joints would not need to perform more work to attenuate similar vertical GRF magnitudes. Even though a smaller vertical GRF occurred when loaded, the increased system mass from the loaded WV might have caused these participants to perceive greater biomechanical task demands when compared to the unloaded condition. Support for this working hypothesis was our observation that the increased system mass from the loaded condition did not alter the mechanical demand placed on these participants, as observed via supplemental calculations of potential energy and statistical comparisons via paired-samples t-tests ($\alpha = 0.05$) and d values. Specifically, the supplemental test revealed similar magnitudes of potential energy in the system at the jump-landing height when loaded versus unloaded (p = 0.540; ES = 0.02; Fig. 1). As such, there appears to be a load-height trade-off as it relates to the biomechanical demand during VJL with and with a loaded WV.

The possible perception of greater biomechanical demands during loaded VJL resulted in the selection of a modified load accommodation strategy (James, Atkins, Dufek, & Bates, 2014; James, Bates, & Dufek, 2003). The modified strategy was characterized by greater torque production by the muscles crossing the hip and ankle joints, since joint work is equal to the product of joint torque and joint angular displacement and the displacement about each joint was not altered by WV use. Thus, the hip and ankle joint
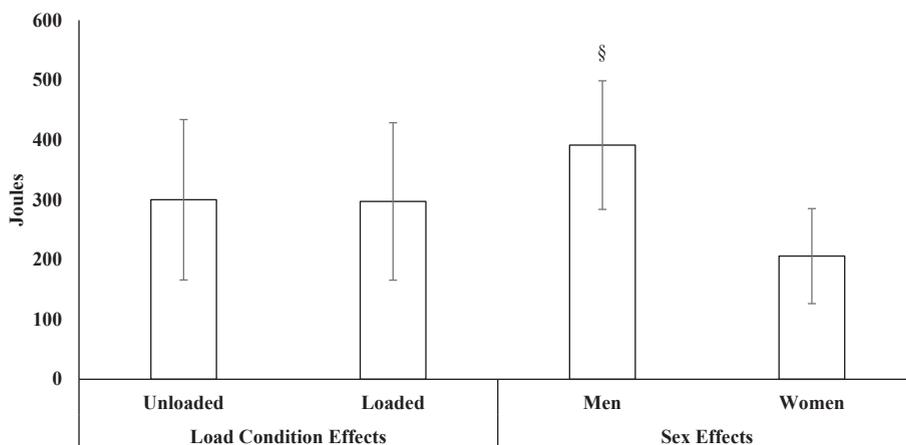

Fig. 1. Supplementary calculations of potential energy for load conditions and sexes. Note: Potential energy was determined by multiplying system mass, gravitational acceleration, and landing height; Load Condition Effects = data for unloaded and loaded conditions with pooled sex data; Sex Effects = data for men and women with pooled load condition data; § = significantly greater than women (p < 0.05).

musculature was working more vigorously (i.e., producing more torque) through an unchanged range of motion during the loaded condition to absorb a similar amount of mechanical energy. It should be noted that these joint work differences between loaded and unloaded conditions might not be meaningful for current or prospective WV users since the differences at the hip and ankle joints were small in magnitude and the difference for total lower extremity work was small. However, it may be that larger magnitude joint work differences between the loaded and unloaded conditions would be revealed if the landing phase was divided into "loading" and "attenuation" sub-phases (Harry, Barker, Eggleston, & Dufek, 2018) or if an initial impact (i.e., first 100 ms of the landing phase) phase (Norcross et al., 2013) was directly assessed. Nonetheless, the current joint work differences between unloaded and loaded conditions should be interpreted cautiously until additional support is presented in the literature.

4.2. Sex effects

When the data were pooled by load condition, the smaller peak vertical GRF and greater total lower extremity work, knee joint work, and ankle joint work values exhibited by women supported our second hypothesis. In addition, the large difference in landing height between sexes was not surprising, since men tend to perform VJL maneuvers with greater jump-landing heights than women (Laffaye, Wagner, & Tombleson, 2014). Contemporary evidence suggests men and women experience similar peak vertical GRF magnitudes during both equal-height landings from elevated platforms (Decker, Torry, Wyland, Sterett, & Steadman, 2003; Weinhandl et al., 2015; Weinhandl et al., 2010) and during VJL with different landing heights accounted for by normalizing the vGRF to kinetic energy (Swartz, Decoster, Russell, & Croce, 2005). However, the lesser peak vertical GRF magnitudes observed herein among women in comparison to men ($\sim 24\%$ less) reflects the influence of lesser absolute landing heights related to sex-specific jumping abilities. The decreased peak vGRF among women was accompanied by lesser biomechanical demands, as evidenced by the previously described supplemental potential energy calculations at maximum jump height with data collapsed by load condition and compared using independent t-tests ($\alpha = 0.05$) and ES values. As could be expected, women exhibited much less potential energy in the system than men did ($p < 0.001$; ES = 2.05; Fig. 1), partially explaining the lesser peak vertical GRF magnitude exhibited by women in comparison to men.

Despite facing lesser biomechanical demands than men faced, women performed a greater amount of total lower extremity work (i.e., more than required to absorb mechanical energy) through greater knee and ankle joint work. Similar to the load condition main effects results, the lack of joint angular displacement differences between sexes indicates women performed the greater than required lower extremity work through the production of greater torque about the knee and ankle joints through the similar ranges of motion. The increased work about the ankle exhibited by these women is consistent with recent work assessing landings from an elevated platform equal to maximum jump height (Weinhandl et al., 2015). Thus, a women-specific distally dominant strategy for mechanical energy absorption appears to exist during landings, regardless of whether they are performed from an elevated platform or following a vertical jump, as long as the landing height is equal to functional capacity. This distally dominant strategy suggests the presence of inefficient landing mechanics in women when compared to men that manifests through lower extremity joint work.

A possible way to address the joint work characteristics among women during VJL may be to employ specific landing strategies that emphasize a focus on external factors rather than internal factors such as body position or muscle function. Such a strategy could encourage a natural governance of motor function (Wulf, McNevin, & Shea, 2001), which can result in more appropriate corrective adjustments (Wulf, Töllner, & Shea, 2007) upon impact with the ground. Promoting the use of external factors has been shown to improve jump-landing technique during the impact phase of drop vertical jumps (Welling, Benjaminse, Gokeler, & Otten, 2016), and such effects could be expected to promote more efficient knee and ankle work during VJL.

5. Limitations

A possible limitation was the absence of additional, heavier load conditions. Including such conditions could have allowed us to determine whether progressively increasing system mass via the WV modifies biomechanical demands similarly to when increasing system mass with other modalities (Suchomel et al., 2016). In addition, additional load conditions might have provided insight into the load-height trade-off, specifically the precise combination of added external loading and corresponding landing height that replicates the biomechanical demands of unloaded VJL. Finally, our choice to smooth kinematic and kinetic data using separate filter cutoffs might have been a limitation, since peak joint torques can be affected by the use of separate filter cutoffs (Kristianslund, Krosshaug, & Van den Bogert, 2012). However, filtering techniques have yet to be assessed during joint work assessments, and it remains difficult to determine whether differences between techniques are solely due to the smoothing of GRF data (Roewer, Ford, Myer, & Hewett, 2014).

6. Conclusions

WV use during VJL coincided with decreased landing height and decreased peak vertical GRF. Despite the actual presence of similar biomechanical demands between loaded and unloaded VJL, a modified load accommodation strategy was observed during VJL. The modified load accommodation strategy was characterized by greater work performed about the hip and ankle joints by way of greater torque production. Despite these outcomes, nearly all of the effect sizes for the joint work differences between loaded and unloaded conditions were small in magnitude, suggesting a need for further investigation before comprehensive conclusions can be presented with respect to joint work differences between VJL with and without a WV. Women were shown to perform the VJL with lesser jump-landing heights and lesser peak vertical GRF than men. However, women also displayed greater work about the knee and

ankle joints through greater torque production. The majority of effect sizes for the joint work differences between men and women were large in magnitude, suggesting the differences between sexes during VJL were meaningful. Thus, these characteristics suggest an inefficient landing strategy for energy absorption about the lower extremity joints in women compared to men. Current and prospective WV users should be aware of their load accommodation strategies during VJL with a WV, and women may consider developing more refined load accommodation strategies regardless of whether or not a WV is used during VJL.

Competing interests

None of the authors declare competing financial interests

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.humov.2018.12.001.

References

Bosco, C., Zanon, S., Rusko, H., Dal Monte, A., Bellotti, P., Latteri, F., ... Pozzo, R. (1984). The influence of extra load on the mechanical behavior of skeletal muscle. *European Journal of Applied Physiology and Occupational Physiology, 53*, 149–154.

Decker, M. J., Torry, M. R., Wyland, D. J., Sterett, W. I., & Steadman, J. R. (2003). Gender differences in lower extremity kinematics, kinetics and energy absorption during landing. *Clinical Biomechanics, 18*, 662–669.

Dempsey, P. C., Handcock, P. J., & Rehrer, N. J. (2014). Body armour: The effect of load, exercise and distraction on landing forces. *Journal of Sports Sciences, 32*, 301–306.

Devita, P., & Skelly, W. A. (1992). Effect of landing stiffness on joint kinetics and energetics in the lower extremity. *Medicine & Science in Sports & Exercise, 24*, 108–115.

Dufek, J. S., & Bates, B. T. (1990). The evaluation and prediction of impact forces during landings. *Medicine & Science in Sports & Exercise, 22*, 370–377.

Faul, F., Erdfelder, A., Lang, A.-G., & Buchner, A. (2009). G*Power: A flexible statistical power analysis program for the social, behavioral, and miomedical sciences. *Behavior Research Methods, 39*, 175–191.

Harry, J. R., Barker, L. A., Eggleston, J. D., & Dufek, J. S. (2018). Evaluating performance during maximum effort vertical jump landings. *Journal of Applied Biomechanics* Epub ahead of print.

Harry, J. R., Barker, L. A., Mercer, J. A., & Dufek, J. S. (2017). Vertical and horizontal impact force comparison during jump-landings with and without rotation in NCAA Division 1 male soccer players. *The Journal of Strength and Conditioning Research, 31*(7), 1780–1786.

Harry, J. R., Freedman Silvernail, J., Mercer, J. A., & Dufek, J. S. (2017). Comparison of pre-contact joint kinematics and vertical impulse between vertical jump-landings and step-off landings from equal heights. *Human Movement Science, 56*, 88–97.

Harry, J. R., Freedman Silvernail, J., Mercer, J. A., & Dufek, J. S. (2018). Bilateral comparison of vertical jump landings and step-off landings from equal heights. *The Journal of Strength and Conditioning Research, 32*, 1937–1947.

Hopkins, W. G. (2006). A new view of statistics: A scale of magnitudes for effect statistics. Available from: http://sportsci.org/resource/stats/effectmag.html.

James, C. R., Atkins, L. T., Dufek, J. S., & Bates, B. T. (2014). An exploration of load accommodation strategies during walking with extremity-carried weights. *Human Movement Science, 35*, 17–29.

James, C. R., Bates, B. T., & Dufek, J. S. (2003). Classification and comparison of biomechanical response strategies for accommodating landing impact. *Journal of Applied Biomechanics, 19*, 106–118.

Janssen, I., Sheppard, J. M., Dingley, A. A., Chapman, D. W., & Spratford, W. (2012). Lower extremity kinematics and kinetics when landing from unloaded and loaded jumps. *Journal of Applied Biomechanics, 28*(6), 687–693.

Khlifa, R., Aouadi, R., Hermassi, S., Chelly, M. S., Jlid, M. C., Hbacha, H., & Castagna, C. (2010). Effects of a plyometric training program with and without added load on jumping ability in basketball players. *The Journal of Strength and Conditioning Research, 24*, 2955–2961.

Kristianslund, E., Krosshaug, T., & Van den Bogert, A. J. (2012). Effect of low pass filtering on joint moments from inverse dynamics: Implications for injury prevention. *Journal of Biomechanics, 45*, 666–671.

Kulas, A., Zalewski, P., Hortobagyi, T., & DeVita, P. (2008). Effects of added trunk load and corresponding trunk position adaptations on lower extremity biomechanics during drop-landings. *Journal of Biomechanics, 41*, 180–185.

Laffaye, G., Wagner, P. P., & Tombleson, T. I. (2014). Countermovement jump height: Gender and sport-specific differences in the force-time variables. *The Journal of Strength & Conditioning Research, 28*, 1096–1105.

Lake, J. P., Mundy, P. D., Comfort, P., McMahon, J. J., Suchomel, T. J., & Carden, P. (2018). The effect of barbell load on vertical jump landing force-time characteristics. *The Journal of Strength & Conditioning Research* Epub ahead of print.

Lees, A., Vanrenterghem, J., & De Clercq, D. (2004). Understanding how an arm swing enhances performance in the vertical jump. *Journal of Biomechanics, 37*, 1929–1940.

McGee, A., Qureshi, A., & Porter, K. (2004). Review of the biomechanics and patterns of limb fractures. *Trauma, 6*, 29–40.

McNitt-Gray, J. (1991). Kinematics and impulse characteristics of drop landing from three heights. *International Journal of Sport Biomechanics, 7*, 201–224.

Mosier, E. M., Fry, A. C., & Lane, M. T. (2017). Kinetic contributions of the upper limbs during counter-movement vertical jumps with and without arm swing. *The Journal of Strength & Conditioning Research* Epub ahead of print.

Norcross, M. F., Blackburn, J. T., Goerger, B. M., & Padua, D. A. (2010). The association between lower extremity energy absorption and biomechanical factors related to anterior cruciate ligament injury. *Clinical Biomechanics, 25*, 1031–1036.

Norcross, M. F., Lewek, M. D., Padua, D. A., Shultz, S. J., Weinhold, P. S., & Blackburn, J. T. (2013). Lower extremity energy absorption and biomechanics during panding, Part I: Sagittal-plane energy absorption analyses. *Journal of Athletic Training, 48*, 748–756.

Nordin, A. D., Dufek, J. S., James, C. R., & Bates, B. T. (2017). Classifying performer strategies in drop landing activities. *Journal of Sports Sciences, 35*(18), 1858–1863.

Roewer, B. D., Ford, K. R., Myer, G. D., & Hewett, T. E. (2014). The 'impact'of force filtering cut-off frequency on the peak knee abduction moment during landing: Artefact or 'artifiction'? *British Joural of Sports Medicine, 48*(6), 464–468.

Sell, T. C., Chu, Y., Abt, J. P., Nagai, T., Deluzio, J., McGrail, M. A., ... Lephart, S. M. (2010). Minimal additional weight of combat equipment alters air assault soldiers'

    landing biomechanics. *Military Medicine, 175*, 41–47.

Smith, R. E., Paquette, M. R., Harry, J. R., Powell, D. W., & Weiss, L. W. (2018). Footwear and sex differences in performance and joint kinetics during maximal vertical jumping. *The Journal of Strength & Conditioning Research* Epub ahead of print.

Suchomel, T. J., Taber, C. B., & Wright, G. A. (2016). Jump shrug height and landing forces across various loads. *International Journal of Sports Physiology and Performance, 11*, 61–65.

Sullivan, G. M., & Feinn, R. (2012). Using effect size-or why the P value is not enough. *Journal of Graduate Medical Education, 4*, 279–282.

Swartz, E. E., Decoster, L. C., Russell, P. J., & Croce, R. V. (2005). Effects of developmental stage and sex on lower extremity kinematics and vertical ground reaction forces during landing. *Journal of Athletic Training, 40*, 9–14.

Thompsen, A. G., Kackley, T., Palumbo, M. A., & Faigenbaum, A. D. (2007). Acute effects of different warm-up protocols with and without a weighted vest on jumping performance in athletic women. *The Journal of Strength & Conditioning Research, 21*, 52–56.

Vincent, W., & Weir, J. (2012). *Statistics in kinesiology* (4th ed.). Champaign, IL: Human Kinetics.

Weinhandl, Irmischer, B. S., & Sievert, Z. A. (2015). Sex differences in unilateral landing mechanics from absolute and relative heights. *The Knee, 22*(4), 298–303.

Weinhandl, H., Joshi, M., & O'Connor, K. M. (2010). Gender comparisons between unilateral and bilateral landings. *Journal of Applied Biomechanics, 26*, 444–453.

Welling, W., Benjaminse, A., Gokeler, A., & Otten, B. (2016). Enhanced retention of drop vertical jump landing technique: A randomized controlled trial. *Human Movement Science, 45*, 84–95.

Wulf, G., McNevin, N., & Shea, C. H. (2001). The automaticity of complex motor skill learning as a function of attentional focus. *The Quarterly Journal of Experimental Psychology: Section A, 54*, 1143–1154.

Wulf, G., Töllner, T., & Shea, C. H. (2007). Attentional focus effects as a function of task difficulty. *Research Quarterly for Exercise and Sport, 78*, 257–264.

Yeow, C. H., Lee, P. V. S., & Goh, J. C. H. (2011). An investigation of lower extremity energy dissipation strategies during single-leg and double-leg landing based on sagittal and frontal plane biomechanics. *Human Movement Science, 30*, 624–635.

Zhang, S. N., Bates, B. T., & Dufek, J. S. (2000). Contributions of lower extremity joints to energy dissipation during landings. *Medicine and Science in Sports and Exercise, 32*, 812–819.