

Article

Beyond Jump Height: Load-Dependent Effects of Lightweight Wearable Resistance on Countermovement and Drop Jump Biomechanics

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Abstract

Of interest were the acute effects of lightweight lower-limb wearable resistance (WR) on the kinematics and kinetics of the countermovement jump (CMJ) and drop jump (DJ). Twenty male athletes (age: 18.05 ± 0.6 years; body mass: 76.4 ± 7.6 kg; height: 182.4 ± 5 cm) performed the CMJ and DJ under four loading conditions: 0%, 2%, 4%, and 6% body mass (BM). Variables of interest included jump height (JH), countermovement depth (CMD), total SSC duration (TCT/GCT), eccentric and concentric phase durations, relative concentric impulse (rCI), relative concentric mean force (rCMF), relative concentric mean power (rCMP), and concentric force index (CFI). Two-way repeated-measures ANOVAs were used to assess jump $\times$ load interactions, with Bonferroni-adjusted pairwise comparisons and planned contrasts used to examine within-jump and between-jump load responses, respectively. Significant jump $\times$ load interactions were observed for all variables analysed. In the CMJ, JH significantly decreased across all loaded conditions, including an 8.3% reduction with 2% BM. In contrast, DJ JH was preserved at 2% BM but significantly decreased at 4% and 6% BM. However, 2% BM was sufficient to increase DJ GCT and ConT, and reduce rCMF, CFI, and rCMP ($p < 0.05$). The change in JH differed between jumps at 2% BM only, whereas changes in CMD, rCMF, CFI, and rCMP differed between jumps across all WR loads. It appears that lightweight WR produces distinct jump-specific responses. Greater initial changes in CMJ JH and CMD suggest that WR altered countermovement strategy before substantially impairing concentric force production, whereas in the DJ, WR altered fast SSC force–time variables before reducing JH. When utilising WR to improve JH performance, practitioners should therefore avoid interpreting JH in isolation and monitor temporal variables (GCT/TCT/ConT/EccT), CMD, rCMF, rCMP and CFI.

Keywords: stretch-shortening cycle; fast SSC; slow SSC



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1. Introduction

To produce powerful athletic movements, the stretch-shortening cycle (SSC) is often utilised. This is a naturally occurring process of muscle function, characterised by an initial preceding eccentric contraction, a short amortisation phase and a potentiated concentric contraction. This preceding eccentric contraction leads to greater force, velocity, and power [1–6]. Multiple mechanisms have been suggested to explain the SSC performance enhancement, involving both mechanical and neural mechanisms such as elastic energy reutilization, stretch reflexes, pre-activation, and residual force enhancement. However, the

relative contributions of these mechanisms remain a topic of debate and vary depending on the variables and the SSC task being assessed [7–9]. Regardless, SSC enhancement can partly be attributed to the ability of the structural elements of the muscle–tendon unit (MTU) to store energy during the eccentric phase and reutilise this stored energy during the concentric phase.

The theoretical framework provided by Hill’s three-component model (TCM) [10] provides insights into the mechanical force transmission of the MTU during the SSC. The TCM consists of three elements: the contractile component (CC), which actively generates force through the contraction of actin and myosin filaments; the series elastic component (SEC), which transmits force through elastic tissues in series with the CC such as tendons; and the parallel elastic component (PEC), consisting of connective tissues such as the endomysium, perimysium, and epimysium that operate in parallel with the CC. These components interact dynamically during SSC movements, and their contributions can vary based on the movement’s velocity, amplitude and mechanical demands [11–14].

The drop jump (DJ) and countermovement jump (CMJ) are two commonly utilised jumps to evaluate lower body SSC performance [15,16]. Although both involve an eccentric loading phase, followed by concentric propulsion, they differ substantially in temporal and biomechanical demands. The predominant distinction between these two jumps is that they are often categorised into fast SSC (<250 ms) and slow SSC (>250 ms) movements based on either DJ ground contact time (GCT) or CMJ total contraction time (TCT). However, they also differ in movement amplitude, velocities, and joint contribution. The DJ is characterised by a smaller movement amplitude, shorter GCT, and greater ankle contribution, whereas the CMJ involves a larger countermovement, longer TCT, and greater contribution from the hip and knee MTUs [17–20]. Due to the limited time to produce force, a well performed DJ relies heavily on pre-activation and isometric contraction of the CC and effective re-utilisation of the energy stored in the SEC [11,12]. In contrast, the larger countermovement and longer TCT of the CMJ, which can vary between 350 and 1300 ms [8,16], allow for greater CC and therefore PEC lengthening, potentially enabling greater elastic energy storage in the PEC. Therefore, although both jumps assess SSC function, they likely reflect different force transmission strategies and may provide different diagnostic insight.

Training strategies aimed at improving lower-body SSC capabilities often incorporate external loading to challenge the MTU. However, the effects of external load on SSC performance are complex and depend on factors such as the magnitude of the load and its distribution. Earp et al. [21] observed that as loading increases, tendon strain decreases significantly during the SSC. It is thought that the SEC acts as a power amplifier at lighter loads whereas at heavier loads the tendon becomes a more rigid force transducer. Due to this, the contribution of the SSC to power output decreases with heavy loading [7]. Additionally, adding load has been shown to result in longer GCT in the DJ [22] and may lead to increased stress on the MTU and joints [23,24], potentially impairing SSC function [25].

One type of external loading is wearable resistance (WR), a training tool that allows for micro-loading of the body during dynamic movements, providing a more specific and sport-relevant stimulus than traditional external loading methods [26]. Unlike barbells or elastic bands, WR loads can be strategically placed on different parts of the body, enabling high-velocity movements that are critical for enhancing SSC performance. WR has also been investigated across a range of sport-specific contexts, including sprint acceleration, change of direction, and throwing performance, supporting its potential as a practical method of overloading high-velocity athletic movements [27–29]. However, despite growing interest in WR, the impact of lightweight lower-limb WR on different SSC movements remains unclear, particularly regarding how varying loads affect fast versus slow SSC movements.

Previously, Macadam et al. [26] investigated the effect of upper and lower limb WR on the CMJ and DJ and observed that with loads less than 6% body mass (BM) there was no significant effect of load placement. Furthermore, jump height (JH), relative peak power, and peak velocity decreased for the 3% and 6% BM loads for both the DJ and CMJ. However, there was no comparison of temporal variables such as DJ GCT and CMJ TCT, countermovement depth (CMD), or concentric mean force/power variables. Therefore, further investigation into how WR affects the propulsive characteristics of these jumps is warranted.

Given the distinct nature of each jump, the primary aim of this study was to further understand how WR affects the kinetics and kinematics of the CMJ and DJ at 2%, 4%, and 6% BM. These loads were selected to investigate practical acute loading responses. The 2% BM condition extends below the 3% BM load previously examined by Macadam et al. [26], whereas the 6% BM condition represented the heaviest practical option with the lower-limb Lila™ Exogen™ setup, allowing progressive increments while maintaining the lightweight nature of the WR stimulus. Due to their differing temporal and biomechanical characteristics, it was hypothesised that the CMJ and DJ would exhibit differential load-dependent responses across key kinematic and kinetic variables.

2. Materials and Methods

2.1. Experimental Approach

An experimental cross-sectional design was used to investigate the effect of additional load (0%, 2%, 4% and 6% BM) on the kinematics and kinetics of CMJ and DJ performance in 20 male athletes. Two-way repeated-measures ANOVAs were used to assess the effects of jump type (CMJ, DJ), load (0%, 2%, 4%, and 6% BM), and the jump $\times$ load interaction for each dependent variable.

2.2. Participants

Twenty male athletes from various sports (age: 18.05 ± 0.6 years; weight: 76.4 ± 7.6 kg; height: 182.4 ± 5 cm) volunteered to participate in this study. The sample size was informed by previous acute WR research using comparable repeated-measures vertical jump protocols, including Macadam et al. [26], who also utilised 20 participants. The cohort included athletes from a diverse range of sports, including rugby, football, cricket, hockey, tennis, basketball, and athletics. All participants were free of medical issues or injuries that could compromise performance and had at least 2 years of structured training in their primary sport. Experience with plyometric training varied across participants; however, none had prior experience with loaded jumping or WR. Participants were informed of the protocol and procedures prior to their involvement, with written informed consent obtained from participants aged 18 years and older, and written parental/guardian consent and participant assent obtained for those under 18 years of age. The Institutional Ethics Committee of Auckland University of Technology provided approval for this study. The study was conducted in accordance with the Declaration of Helsinki and approved by the Auckland University of Technology Ethics Committee (AUTEC 20/105).

2.3. Equipment

Participants were loaded using Lila™ Exogen™ exoskeleton suits (Sportboleh Sdh Bhd, Kuala Lumpur, Malaysia). The Exogen™ exoskeleton suit allows load to be attached in multiple positions through the addition of fusiform shaped loads of 100 g and 200 g. Load was attached to the lower body using compression shorts and a pair of calf sleeves (Figure 1). Two thirds of the load was distributed evenly around the thigh and the remaining 1/3 distributed on the anterior and posterior surfaces of the shank of the leg [26]. The total

mass of added load was 2%, 4% or 6% of each participant's body mass calculated to the closest 100 g.



Figure 1. Lila™ Exogen™ wearable resistance.

2.4. Vertical Jump Testing

All vertical jump testing took place during a single session. Participants were required to avoid stressful physical activity for 24 h beforehand. Prior to testing, subject information [age, BM (scales) and height (stadiometer)] was collected. Participants were informed of the procedures and familiarised with each vertical jump test until technique was verified as correct by the researcher. Following a standardised warm-up consisting of dynamic lower-body movements (8 squats, 8 walking lunges per side, 10 leg swings per side, 10 calf raises, and 15 pogo jumps), and two practice trials of each jump type, each participant completed the vertical jump testing protocol. Each subject was required to complete a total of 24 jumps (4 loading conditions $\times$ 2 jump conditions $\times$ 3 jumps). The unloaded CMJ and DJ assessments were completed first. Following this, the order of jump type and WR loading condition (2%, 4%, and 6% BM) was randomised for each participant. Thereafter, participants performed three consecutive trials for each jump/load condition in a randomised order. Each consecutive trial was separated by at least 30 s and each jump condition by at least a 2 min rest period [30]. Of the three trials performed in each condition, two trials were selected and averaged for analysis. For the CMJ, the two trials with the greatest JH were selected. For the DJ, trials with a GCT $\leq$ 250 ms were prioritised, with the two trials demonstrating the greatest jump height among those meeting this criterion selected. Where fewer than two trials achieved a GCT $\leq$ 250 ms, trials with the shortest GCT were prioritised, with JH used as a secondary selection criterion.

To improve the reliability of the data, participants were instructed to jump with the knees and ankles extended and land in a similarly extended position [31]. To limit the impact of instructions on performances, consistent instructions were provided to all participants during each vertical jump trial [32]. All participants were instructed to ‘jump as high and fast as possible off the force plate’ for each jump variation. All jumps were performed with hands on hips to prevent the use of arms and attain true measures of leg force–time variables [32]. If the subject removed their hands from hips, displayed excessive knee flexion whilst airborne or landed in an incorrect position the jump was declared invalid and repeated after adequate rest.

Prior to the CMJ participants stood with feet hip-width apart on the force plate for 2–3 s to determine system weight, which was used for analysis. Participants initiated the

jump with a self-selected countermovement depth. An approximate 90° knee angle was provided as a general technique cue but was not controlled or used as a validity criterion. Participants then immediately performed a maximal effort VJ with no pause between the eccentric and concentric phases. The DJ was performed from a standardised height of 30 cm [33] to provide a practical fast SSC stimulus while limiting excessive landing demands and maintaining consistency across loading conditions. During the DJ, subjects were instructed to step out and fall onto the force platform and were additionally cued to minimise GCT. After the second landing, participants were required to stand still for 2–3 s to attain the system weight which was used for analysis.

2.5. Data Collection

All vertical jump data was collected with a portable force plate (AMTI, ACP, Watertown, MA, USA) using a sampling rate of 1000 Hz. Raw vertical ground reaction force (vGRF) data was analysed using ForceDecks software V2.0.9064 (VALD, Brisbane, Australia) to calculate the variables of interest. Default ForceDecks processing settings available at the time of data collection were used, with no additional filtering or custom processing applied prior to analysis. Initiation of the CMJ was defined as the point when total vGRF deviated −20 N from system weight. Initiation of the landing of the DJ was when vGRF exceeded 20 N. All take-offs were identified as the instant when vGRF fell below 10 N. The impulse–momentum relationship was used to calculate JH. Where appropriate, TCT and GCT were divided into eccentric phase duration (EccT) and concentric phase duration (ConT). The start of ConT was determined when velocity of the centre of mass became positive. Relative concentric impulse (rCI), relative concentric mean force (rCMF), and relative concentric mean power (rCMP) were calculated relative to system mass (BM + WR). The concentric force index (CFI) was calculated as below:

$$CFI = \frac{rCMF}{ConT} \times 100$$

2.6. Statistical Analysis

Means and standard deviations were used as measures of centrality and spread of data. Normality and outlier analysis were undertaken on these means. Normality was assessed using the Shapiro–Wilk test. Sphericity was assessed using Mauchly’s test; when sphericity was violated, Greenhouse–Geisser-adjusted values were utilised. Within-session reliability was assessed using coefficient of variation (CV; SD/mean × 100).

Two-way repeated-measures ANOVAs were used to assess the effects of jump type (CMJ, DJ), load (0%, 2%, 4%, and 6% BM), and the jump × load interaction for each dependent variable. For this analysis, CMJ TCT and DJ GCT were treated as jump-specific measures of total SSC duration. Effect sizes for two-way repeated-measures ANOVA were reported as partial eta squared (partial η^2). Partial η^2 values were interpreted using conventional thresholds of small (≥ 0.01), medium (≥ 0.06), and large (≥ 0.14) [34,35].

Where a statistically significant jump × load interaction was observed, Bonferroni-adjusted pairwise comparisons were used to examine differences between loading conditions within each jump type. Percentage changes were calculated relative to the unloaded (0% BM) condition for each jump type as

$$\% \text{ Change} = \frac{\text{Loaded condition} - 0\% \text{ BM Condition}}{0\% \text{ BM Condition}} \times 100$$

Planned contrasts between the CMJ and DJ were used to compare the change from 0% BM to each WR loading condition (2%, 4%, and 6% BM). For each contrast, the between-jump difference in change, 95% confidence interval, and two-sided *p*-value were reported.

Statistical significance was accepted at $p < 0.05$. SPSS 29.0 (SPSS Inc., Chicago, IL, USA) was used for statistical analysis.

3. Results

3.1. Overall Effects of Jump Type and Load

The two-way repeated-measures ANOVA results for the jump $\times$ load interactions are presented in Table 1. Statistically significant jump $\times$ load interactions were observed for all variables analysed.

Table 1. Two-way repeated-measures ANOVA results for jump $\times$ load interactions.

Variable	df	F	p	Partial η^2
JH (cm)	2.085, 39.609	4.086	0.023	0.177
CMD (cm)	3, 57	10.056	<0.001	0.346
TCT/GCT (CMJ/DJ ms)	2.195, 41.697	6.419	0.003	0.253
EccT (ms)	2.138, 40.617	5.913	0.005	0.237
ConT (ms)	3, 57	3.120	0.033	0.141
rCI (Ns/kg)	2.051, 38.963	3.644	0.034	0.161
rCMF (N/kg)	2.114, 40.173	10.744	<0.001	0.361
CFI	3, 57	13.692	<0.001	0.419
rCMP (W/kg)	1.921, 36.490	15.322	<0.001	0.446

Note. Abbreviations: CFI = concentric force index; CMD = countermovement depth; ConT = concentric phase duration; EccT = eccentric phase duration; GCT = ground contact time; JH = jump height; rCI = relative concentric impulse; rCMF = relative concentric mean force; rCMP = relative concentric mean power; TCT = total contraction time.

3.2. Load-Dependent Responses Within the CMJ and DJ

Descriptive values and Bonferroni-adjusted pairwise comparisons for the CMJ and DJ are presented in Tables 2 and 3, respectively, with within-session CVs ranging from 1.1 to 5.8% for the CMJ and 2.8 to 7.3% for the DJ. Within the CMJ, JH and CMD were significantly lower for all loaded conditions compared with 0% BM ($p < 0.05$). TCT and EccT were significantly lower at 2% BM, but did not differ significantly from 0% BM at 4% or 6% BM whereas ConT did not significantly differ from 0% BM at any load. Further, rCI was significantly lower for all loaded conditions, whilst rCMF was only significantly lower at 6% BM. CFI did not significantly differ for any loading condition as compared to 0% BM, and rCMP was significantly lower at 4% and 6% BM.

Table 2. Kinematic and kinetic variables during the CMJ for all loading conditions.

Variable	0%	2%	4%	6%
JH (cm)	37.6 $\pm$ 3.4 _{bcd}	34.5 $\pm$ 3.6 _{ad}	34.0 $\pm$ 3.6 _{ad}	32.7 $\pm$ 3.2 _{abc}
TCT (ms)	833 $\pm$ 74 _b	788 $\pm$ 95 _{ad}	810 $\pm$ 72	830 $\pm$ 100 _b
CMD (cm)	34.2 $\pm$ 3.6 _{bcd}	31.6 $\pm$ 4.9 _a	31.5 $\pm$ 4.2 _a	31.8 $\pm$ 4.7 _a
EccT (ms)	561 $\pm$ 57 _b	523 $\pm$ 71 _{ad}	542 $\pm$ 56	556 $\pm$ 80 _b
ConT (ms)	271 $\pm$ 22	265 $\pm$ 29	269 $\pm$ 29	274 $\pm$ 28
rCI (Ns/kg)	2.71 $\pm$ 0.12 _{bcd}	2.60 $\pm$ 0.13 _{ad}	2.58 $\pm$ 0.13 _{ad}	2.53 $\pm$ 0.12 _{abc}
rCMF (N/kg)	19.8 $\pm$ 0.9 _d	19.7 $\pm$ 1.1 _d	19.5 $\pm$ 1.1	19.1 $\pm$ 1.0 _{ab}
CFI	7.36 $\pm$ 0.92	7.56 $\pm$ 1.33 _d	7.37 $\pm$ 1.20	7.07 $\pm$ 1.13 _b
rCMP (W/kg)	29.1 $\pm$ 2.4 _{cd}	27.9 $\pm$ 2.6 _d	27.3 $\pm$ 2.6 _a	26.3 $\pm$ 2.2 _{ab}

Note. Abbreviations: CFI = concentric force index; CMD = countermovement depth; ConT = concentric phase duration; EccT = eccentric phase duration; JH = jump height; rCI = relative concentric impulse; rCMF = relative concentric mean force; rCMP = relative concentric mean power; TCT = total contraction time. Subscript letters indicate significant differences between loading conditions ($p < 0.05$): 'a' corresponds to 0%, 'b' to 2%, 'c' to 4%, and 'd' to 6%.

Table 3. Kinematic and kinetic variables during the DJ for all loading conditions.

Variable	0%	2%	4%	6%
JH (cm)	31.9 ± 5.2 _{cd}	31.5 ± 5.3 _{cd}	28.9 ± 5.6 _{ab}	28.6 ± 5.4 _{ab}
GCT (ms)	232 ± 27 _{bcd}	251 ± 36 _a	251 ± 37 _a	254 ± 42 _a
CMD (cm)	17.1 ± 2.1	18.2 ± 2.4	18.2 ± 2.6	18.5 ± 3.2
EccT (ms)	108 ± 14 _c	116 ± 18	117 ± 18 _a	118 ± 21
ConT (ms)	124 ± 16 _{bcd}	135 ± 20 _a	134 ± 21 _a	136 ± 24 _a
rCI (Ns/kg)	2.49 ± 0.21 _{cd}	2.47 ± 0.21 _{cd}	2.37 ± 0.23 _{ab}	2.36 ± 0.23 _{ab}
rCMF (N/kg)	30.1 ± 2.6 _{bcd}	28.4 ± 2.6 _a	27.8 ± 2.6 _a	27.4 ± 2.6 _a
CFI	24.8 ± 5.2 _{bcd}	21.7 ± 4.7 _a	21.5 ± 5.2 _a	20.9 ± 5.2 _a
rCMP (W/kg)	114.7 ± 11.2 _{bcd}	106.9 ± 11.5 _{acd}	102.9 ± 12.0 _{ab}	101.5 ± 11.1 _{ab}

Note. Abbreviations: CFI = concentric force index; CMD = countermovement depth; ConT = concentric phase duration; EccT = eccentric phase duration; GCT = ground contact time; JH = jump height; rCI = relative concentric impulse; rCMF = relative concentric mean force; rCMP = relative concentric mean power. Subscript letters indicate significant differences between loading conditions ($p < 0.05$): 'a' corresponds to 0%, 'b' to 2%, 'c' to 4%, and 'd' to 6%.

With regard to the DJ, JH did not significantly differ from 0% BM at 2% BM but was significantly lower at 4% and 6% BM. GCT and ConT were significantly greater across all loaded conditions, whereas EccT was significantly greater only at 4% BM. Further, CMD did not significantly differ from 0% BM at any load. rCI was significantly lower at 4% and 6% BM, while rCMF, CFI, and rCMP were significantly lower across all loaded conditions.

Additional significant differences between loaded conditions for both the CMJ and DJ are shown in Tables 2 and 3 respectively.

3.3. Load-Specific Differences Between the CMJ and DJ

Planned CMJ-vs-DJ contrasts are presented in Table 4. The change in JH differed significantly between jumps only with 2% BM. For the temporal variables, significant between-jump differences were observed for TCT/GCT, EccT, and ConT at 2% and 4% BM, but not at 6% BM, whereas CMD differed significantly between jumps for all three WR loads. Further, rCI differed significantly between jumps at 2% BM only. In contrast, rCMF, CFI, and rCMP showed significant between-jump differences across 2%, 4%, and 6% BM loading.

Table 4. Load-specific changes from 0% BM and CMJ-vs-DJ contrasts.

Variable	Load	CMJ Change	DJ Change	CMJ-DJ Difference in Change (95% CI)	F(1, 19)	p
JH (cm)	2%	−3.11 (−8.3%)	−0.39 (−1.2%)	−2.72 (−4.66 to −0.78)	8.63	0.008 *
	4%	−3.61 (−9.6%)	−2.93 (−9.2%)	−0.68 (−2.94 to +1.58)	0.40	0.534
	6%	−4.92 (−13.1%)	−3.27 (−10.3%)	−1.66 (−3.66 to +0.34)	3.01	0.099
TCT/GCT (ms)	2%	−45.60 (−5.5%)	+18.93 (+8.2%)	−64.53 (−97.21 to −31.84)	17.08	<0.001 *
	4%	−23.10 (−2.8%)	+18.85 (+8.1%)	−41.95 (−69.93 to −13.97)	9.85	0.005 *
	6%	−3.55 (−0.4%)	+22.32 (+9.6%)	−25.87 (−63.36 to +11.61)	2.09	0.165
CMD (cm)	2%	−2.62 (−7.7%)	+1.10 (+6.4%)	−3.72 (−5.49 to −1.95)	19.35	<0.001 *
	4%	−2.67 (−7.8%)	+1.12 (+6.5%)	−3.79 (−5.36 to −2.22)	25.53	<0.001 *
	6%	−2.35 (−6.9%)	+1.33 (+7.8%)	−3.68 (−5.66 to −1.69)	15.03	0.001 *
EccT (ms)	2%	−38.80 (−6.9%)	+8.20 (+7.6%)	−47.00 (−71.94 to −22.06)	15.56	<0.001 *
	4%	−19.93 (−3.5%)	+9.13 (+8.5%)	−29.05 (−50.76 to −7.34)	7.84	0.011 *
	6%	−5.88 (−1.0%)	+10.03 (+9.3%)	−15.90 (−46.15 to +14.35)	1.21	0.285

Table 4. Cont.

Variable	Load	CMJ Change	DJ Change	CMJ-DJ Difference in Change (95% CI)	F(1, 19)	p
ConT (ms)	2%	−6.80 (−2.5%)	+10.73 (+8.6%)	−17.53 (−28.59 to −6.46)	11.00	0.004 *
	4%	−3.18 (−1.2%)	+9.72 (+7.8%)	−12.90 (−24.93 to −0.87)	5.04	0.037 *
	6%	+2.32 (+0.9%)	+12.30 (+9.9%)	−9.97 (−23.39 to +3.44)	2.42	0.136
rCI (Ns/kg)	2%	−0.11 (−4.2%)	−0.02 (−0.6%)	−0.10 (−0.17 to −0.03)	8.97	0.007 *
	4%	−0.13 (−4.9%)	−0.12 (−4.7%)	−0.02 (−0.11 to +0.08)	0.13	0.721
	6%	−0.18 (−6.7%)	−0.13 (−5.2%)	−0.05 (−0.13 to +0.03)	1.88	0.187
rCMF (N/kg)	2%	−0.13 (−0.7%)	−1.67 (−5.5%)	+1.54 (+0.63 to +2.45)	12.56	0.002 *
	4%	−0.34 (−1.7%)	−2.27 (−7.5%)	+1.93 (+0.98 to +2.88)	18.07	<0.001 *
	6%	−0.73 (−3.7%)	−2.69 (−8.9%)	+1.97 (+0.88 to +3.06)	14.31	0.001 *
CFI	2%	+0.20 (+2.8%)	−3.12 (−12.6%)	+3.33 (+1.82 to +4.84)	21.24	<0.001 *
	4%	+0.01 (+0.1%)	−3.30 (−13.3%)	+3.31 (+1.76 to +4.85)	20.13	<0.001 *
	6%	−0.29 (−3.9%)	−3.95 (−15.9%)	+3.67 (+2.07 to +5.26)	23.20	<0.001 *
rCMP (W/kg)	2%	−1.24 (−4.3%)	−7.82 (−6.8%)	+6.58 (+2.77 to +10.39)	13.05	0.002 *
	4%	−1.79 (−6.2%)	−11.84 (−10.3%)	+10.05 (+5.94 to +14.15)	26.23	<0.001 *
	6%	−2.80 (−9.6%)	−13.23 (−11.5%)	+10.42 (+5.40 to +15.45)	18.83	<0.001 *

Note. Changes are relative to the unloaded (0% BM) condition. Negative values indicate a decrease and positive values an increase. CMJ–DJ difference in change = (CMJ loaded − CMJ 0%) − (DJ loaded − DJ 0%); negative values indicate a lower change in the CMJ relative to the DJ, whereas positive values indicate a lower change in the DJ relative to the CMJ. Values in parentheses for the difference in change represent 95% confidence intervals. * $p < 0.05$.

4. Discussion

The aim of this study was to investigate how WR influenced the kinematics and kinetics of the CMJ and DJ, with a specific focus on whether the two jumps exhibited different responses to loading of 2%, 4%, and 6% BM.

Notable key findings included the following: (1) WR did not influence the CMJ and DJ uniformly, as significant jump $\times$ load interactions were observed for all variables analysed. Planned contrasts provided evidence that these differences were load and variable specific. (2) The CMJ showed a greater reduction in JH with 2% BM, and a distinct change in CMD, with CMD responses differing between jumps across all WR loads. (3) The DJ produced greater increases in temporal variables at lighter loads and greater reductions in relative concentric force and power variables across the loading range. (4) The inclusion of CFI appeared to provide additional information to JH alone, with 2% BM leading to decreased JH and CMD in the CMJ while CFI was preserved, whereas reduced CFI was observed for the DJ despite no significant change in JH.

4.1. Jump-Specific Load Responses to Wearable Resistance

Overall, WR led to distinct load-dependent responses in the CMJ and DJ, as reflected by the significant jump $\times$ load interactions observed for all variables analysed. This supports the broader hypothesis that the two jumps would respond differently to load, although the direction of these effects differed across variables. These differences are likely related to the contrasting movement amplitudes, temporal characteristics, and propulsive demands of each jump.

The CMJ response appeared to be characterised primarily by an early alteration in CMD. With 2% BM, JH decreased significantly (−8.3%) alongside decreased CMD (−7.7%, $p < 0.05$) and shorter EccT (−6.9%, $p < 0.05$), whereas ConT, rCMF, and CFI remained comparatively stable. This suggests that the early reduction in CMJ JH may not reflect a major impairment in concentric force production. Instead, the decrement may have been

influenced by a change in movement strategy, whereby participants performed a shallower and shorter countermovement under load. This is biomechanically relevant because the CMJ relies on a relatively large movement amplitude and longer TCT, which may allow greater active lengthening of the CC and greater contribution from elastic structures during the eccentric phase [3,4,8]. However, the CMJ response was not limited to the 2% BM condition. JH decreased further with 6% BM (-13.1% , $p < 0.05$), which is consistent with Macadam et al. [26], who reported reductions in CMJ JH with 3% (12%) and 6% BM (17%). With greater loads, the effect of WR became more evident. rCI reduced across all loads (-4.2% to -6.7% , $p < 0.05$), rCMP reduced at 4% (-6.2% , $p < 0.05$) and 6% (-9.6% , $p < 0.05$) BM, and rCMF reduced at 6% (-3.7% , $p < 0.05$) BM. Therefore, WR may initially alter the preparatory eccentric strategy of the CMJ, whereas greater loads appear to impair concentric force and power production.

These findings partially align with previous loaded CMJ research showing that external load can alter countermovement strategy. Feeney et al. [36] reported that load (0–40%) decreased CMD and increased ConT. In contrast, Wade et al. [37] reported that heavier vest loads (20–60% BM) increased CMD, allowing athletes to maintain JH. In this study, as little as 2% BM lower-limb WR reduced CMD and EccT without clearly altering ConT or rCMF. This discrepancy suggests that the effect of loading on CMD in the CMJ might differ depending on the load range, with lighter loads (2–6% BM) decreasing CMD while heavier loads (20%+ BM) lead to a deeper countermovement to maintain performance. Therefore, the response to load in the CMJ appears highly dependent on both the amount and distribution of external load.

In contrast, a different load response was noted in the DJ. With 2% BM, DJ JH did not significantly differ from the unloaded condition (-1.2%). However, the 2% BM load led to an increased GCT (8.2%, $p < 0.05$), ConT (8.6%, $p < 0.05$) and decreased rCMF (-5.5% , $p < 0.05$), CFI (-12.6% , $p < 0.05$), and rCMP (-6.8% , $p < 0.05$). This suggests that although participants maintained DJ height with 2% BM WR load, they did so with a longer GCT and reduced relative concentric force and power production. These findings are consistent with previous loaded DJ research showing that external load tends to increase temporal demands and reduce aspects of propulsive performance. For example, Makaruk et al. [22] reported that 5% BM loading increased the time between eccentric and concentric peak power by 4.4–5.8% ($p < 0.05$) across drop heights, while Dempsey et al. [38] observed a 17.5% increase in GCT with an 8.5% BM load. Similarly, Macadam et al. [26] reported significant reductions in DJ JH of approximately 10–14%, relative peak power of 6.4–9.6%, and peak velocity of 3–8% with 3–6% BM WR loading. The present findings extend this work by showing that even 2% BM lower-limb WR was sufficient to alter DJ timing and concentric force–time variables, despite no significant change in JH.

While 2% BM changed the way the DJ was performed without significantly reducing JH, the addition of 4% and 6% BM produced significant JH reductions of 9.2% ($p < 0.05$) and 10.3% ($p < 0.05$), respectively. This suggests lightweight lower-limb WR may first disrupt the temporal and propulsive characteristics of the fast SSC, before heavier loading leads to a measurable decline in JH. Importantly, the relatively similar JH reductions at 4% and 6% BM suggest that the DJ JH response to load was not linear.

The load-specific contrasts provided further support for these differing CMJ and DJ findings. At 2% BM, the reduction in JH was significantly greater in the CMJ, with a between-jump difference of -2.72 cm (95% CI: -4.66 to -0.78), whereas JH responses did not differ significantly between jumps at 4% or 6% BM. The difference in CMD response was more consistent, with CMD differing between jumps for all three WR loads (-3.72 , -3.79 , and -3.68 cm at 2%, 4%, and 6% BM, respectively). This strengthens the interpretation that the CMJ response was characterised by a change in countermovement strategy.

Further, the greater temporal response observed in the DJ was supported by significant between-jump differences in TCT/GCT, EccT, and ConT for 2% and 4% BM. These differences may partly reflect the contrasting constraints of the two tasks. The CMJ has a larger movement amplitude and longer duration over which countermovement strategy can be modified, whereas the DJ is more constrained and provides less opportunity to alter movement amplitude following ground contact. The increase in GCT and ConT observed in the DJ may therefore reflect a greater reliance on extending the time available for force application when additional load was introduced. Notably, the between-jump differences in these temporal variables were no longer significant at 6% BM, whereas differences in rCMF, CFI, and rCMP remained. This suggests that at the highest load, the distinction between jumps was expressed less through phase durations and more through concentric force production. The greater reductions in DJ rCMF and rCMP, together with CFI, were supported by significant between-jump differences across all three WR loads.

In contrast, rCI differed between jumps only at 2% BM. As rCI reflects both the magnitude and duration of force application, the absence of a significant difference in rCI at 4% and 6% BM may indicate that differences in force magnitude were partly offset by differences in the time over which force was applied. This suggests that similar changes in JH and rCI did not necessarily reflect similar changes in movement strategy and force–time characteristics in response to WR. While these findings describe the average response of the cohort, future research should determine whether individual athletes exhibit different acute responses to lightweight WR and whether this influences optimal WR prescription.

4.2. Interpretation of the Concentric Force Index

The observed differences between JH and CFI highlighted the descriptive value of CFI for interpreting the effects of WR. In the CMJ, the combination of reduced JH and CMD with a relatively stable rCMF, ConT, and consequently CFI provides evidence that WR primarily altered the countermovement strategy, rather than a substantial change in relative concentric force production. Similarly, the 12.6% reduction in DJ CFI at 2% BM, despite no significant reduction in JH, reflected the combined reduction in rCMF and increase in ConT. This reduction in CFI reinforces that WR altered DJ propulsive force–time characteristics before producing a clear decrement in outcome performance. Therefore, JH and CFI should be interpreted (alongside rCMF and ConT) as complementary rather than interchangeable variables. This distinction is particularly important when WR is added, as the outcome of the jump may remain relatively stable while the demands of the task change. A given JH achieved with additional load does not necessarily represent the same mechanical demand as the same JH achieved unloaded, because the athlete must accelerate a greater system mass. Therefore, metrics derived primarily from JH may underrepresent the effect of WR when movement outcome is preserved but the underlying force–time strategy is altered. By incorporating rCMF and ConT, CFI provides a simple description of how relative force was produced over the concentric phase, rather than an independent measure of force–time behaviour.

The contrast between CFI and rCI is also useful when interpreting these responses. Although both describe aspects of concentric force–time performance, time contributes differently to each measure. A longer ConT provides more time over which impulse can be produced, whereas the same increase in ConT contributes to a lower CFI because ConT forms the denominator of the calculation. Therefore, increasing the time available for force application may partly offset reductions in force when considering rCI, while simultaneously contributing to a reduction in CFI. This may help explain why rCI responses became more similar between jumps at 4% and 6% BM, while significant between-jump differences in CFI remained across the loading range.

Further, CFI was also used because reactive strength index (RSI) cannot be applied equivalently to the CMJ and DJ. RSI is specific to rebound-type tasks such as the DJ, whereas CMJ performance is typically assessed using reactive strength index modified (RSImod). Although these metrics are conceptually related, they are not directly comparable. While the preceding eccentric phase differs between the CMJ and DJ, both ultimately require the athlete to express force rapidly during propulsion. Therefore, CFI focuses on the concentric phase available with both jumps, allowing a more consistent comparison. This does not replace JH, RSI, or RSImod, but provides a common descriptive measure that can be interpreted alongside JH, rCMF, and ConT when load alters how a jump is performed.

4.3. Theoretical Three-Component Model Interpretation

From a TCM perspective, the reduced CMD observed in the CMJ may have limited the active lengthening of the CC and PEC, providing one possible explanation for the early reduction in JH. In contrast, the DJ is an ankle-dominant, fast SSC movement that relies on short GCT, pre-activation, and rapid force transmission through the SEC [11,13,17,19]. Effective DJ performance therefore relies on the CC maintaining sufficient stiffness during ground contact, allowing the SEC to rapidly store and reutilise elastic energy. Earp et al. [21] demonstrated that during knee extensor SSC exercise tendon strain decreased as loading intensity increased, suggesting that the SEC may shift from acting as a power amplifier at lighter loads toward a more rigid force transmitter at heavier loads. Although this was not examined during vertical jumping or WR loading, it provides a useful mechanistic framework for interpreting these results. Specifically, the increase in DJ ConT, reduction in CFI, and negligible change in JH at 2% BM may suggest that athletes preserved the impulse required for jump performance by increasing the time available to produce force. From a TCM perspective, this pattern is consistent with a shift away from rapid SEC-dominant recoil and toward greater active force generation by the CC during propulsion. Therefore, WR may not have immediately reduced DJ JH but may have altered the relative interaction of the CC and SEC underlying the fast SSC movement.

However, this interpretation remains theoretical because muscle activation, fascicle behaviour, tendon length changes, and joint-level kinetics were not directly measured. It is also important to acknowledge that the observed changes are also likely accompanied by neural factors, including changes in pre-activation, stretch-reflex contribution, intermuscular coordination, or protective inhibition [7–9,39]. This may be particularly relevant for the DJ, where additional load increases braking demands during landing. Therefore, the longer ConT and reduced rCMF observed under WR may reflect a protective strategy.

4.4. Limitations and Future Research

Several limitations should be considered when interpreting these findings. First, the sample consisted of 20 young male athletes, which limits generalisability to female athletes, older populations, youth athletes, or athletes from different training backgrounds. Differences in tendon compliance, strength, coordination, and SSC strategy may influence how individuals respond to WR loading.

Second, all unloaded trials were performed before the loaded trials. Although this ensured that unloaded baseline performance was not influenced by prior loaded jumps, the non-randomised sequence may have introduced order effects. While we aimed to minimise these effects through standardised warm-up procedures and rest periods, it is not possible to determine whether the observed changes were entirely due to WR or were partly influenced by learning, fatigue, or potentiation.

Third, the DJ was performed from a single 30 cm drop height. While this was standardised and practical, it may not have represented the optimal drop height for all participants.

Some participants may have been under- or over-loaded by the drop height before WR was even added. Future researchers should therefore consider the use of individually optimised or multi-height drop-jump protocols to better account for individual differences in fast SSC performance.

Fourth, this study did not directly measure muscle activation, fascicle behaviour, tendon length changes or joint-level kinetics. Therefore, interpretations regarding the CC, SEC, and PEC should be viewed as theoretical explanations based on external force–time variables rather than direct evidence of MTU behaviour. Future studies using electromyography, ultrasound, and joint-level biomechanical modelling would provide greater insight into whether the observed changes reflect altered pre-activation, protective inhibition, fascicle shortening velocity, tendon energy storage, or changes in joint contribution.

Finally, velocity variables were not reported in the present analysis, limiting the ability to determine whether reductions in rCMP were primarily force- or velocity-mediated. Including concentric mean velocity or velocity at peak power in future analyses would strengthen the interpretation of power changes under WR loading.

Future researchers should also investigate WR limb loading below 2% BM. As 2% BM was already sufficient to alter key variables in both jumps, smaller loading increments may help identify lower loads at which acute changes in jump performance and force–time characteristics become evident. Further, the variables identified as most receptive to WR loading provide training foci for future research. Long-term training studies are needed to determine whether repeated WR exposure drives adaptation, and whether that adaptation transfers to improvements in unloaded JH and other outcome measures. In this cohort, mean DJ GCT exceeded the commonly used 250 ms fast SSC threshold under each loaded WR condition. Future researchers should therefore investigate whether training with lightweight WR that increases GCT beyond this threshold can still improve subsequent unloaded fast SSC performance.

4.5. Practical Applications

Based on the acute responses observed in this study, WR prescription should be jump-specific, load-specific, and aligned with the desired training stimulus according to the SSC quality being targeted. A practical approach would be to first assess unloaded CMJ and DJ performance, then repeat the same jumps with a light WR load, for example 2% BM, while monitoring both outcome and strategy variables. This approach would allow practitioners to determine whether the load is preserving or substantially altering jump performance, countermovement strategy or force–time characteristics. Importantly, JH should not be interpreted in isolation. For the DJ, coaches should monitor GCT, ConT, rCMF, CFI, and rCMP where possible. For the CMJ, practitioners should monitor whether reductions in JH are accompanied by reductions in CMD. Given the potential for individual variation in response to lightweight WR, practitioners should use these variables to monitor each athlete's response and adjust WR loading accordingly, rather than relying solely on group-based analysis.

5. Conclusions

In conclusion, lightweight lower-limb WR produced distinct load-dependent responses in the CMJ and DJ. At 2% BM, the reduction in JH was greater in the CMJ, while CMD responses differed between jumps across all WR loads. In contrast, greater temporal responses at the lighter loads and greater reductions in rCMF, CFI, and rCMP across the loading range were observed in the DJ. Importantly, although between-jump differences in JH were not significant at 4% and 6% BM, differences in rCMF and rCMP remained

significantly different. Therefore, similar changes in JH did not necessarily reflect similar movement strategies or force–time responses to WR.

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Abbreviations

The following abbreviations are used in this manuscript:

BM	Body mass
CC	Contractile component
CFI	Concentric force index
CMD	Countermovement depth
CMJ	Countermovement jump
ConT	Concentric phase duration
DJ	Drop jump
EccT	Eccentric phase duration
GCT	Ground contact time
JH	Jump height
MTU	Muscle–tendon unit
PEC	Parallel elastic component
rCI	Relative concentric impulse
rCMF	Relative concentric mean force
rCMP	Relative concentric mean power
RSI	Reactive strength index
RSImod	Reactive strength index modified
SEC	Series elastic component
SSC	Stretch-shortening cycle
TCM	Three-component model
TCT	Total contraction time
vGRF	Vertical ground reaction force
WR	Wearable resistance

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