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Effects of handheld dumbbell load on force-time characteristics during countermovement jumps with accentuated eccentric loading in youth athletes

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ABSTRACT

The purpose of this study was to examine the effects of handheld dumbbell load on force-time characteristics during countermovement jumps with accentuated eccentric loading (CMJ_{AEL}). Nineteen youth athletes (9 males and 10 females; age 15 ± 2 years; stature 1.66 ± 0.09 m; body mass 54.8 ± 8.4 kg) performed bodyweight CMJs (CMJ_{BW}) followed by CMJ_{AEL} conditions at 20% (CMJ_{AEL20}) and 30% (CMJ_{AEL30}) of body mass. Vertical ground reaction force (vGRF) data were analysed using a combined forward and backward integration method to account for changes in system mass. Jump height increased in both CMJ_{AEL} conditions compared with CMJ_{BW}, with the greatest improvement during CMJ_{AEL20}. Propulsion time increased with load, while propulsion mean vGRF decreased, suggesting participants produced force over a longer duration to attain a greater jump height. Propulsion mean velocity and power increased under CMJ_{AEL20} but changes were uncertain for CMJ_{AEL30}. Braking responses were inconsistent, as higher braking vGRF were not accompanied by meaningful changes in braking velocity or power. These findings suggest CMJ_{AEL} can acutely increase jump height; however, associated changes in force-time characteristics, particularly phase durations and velocities, should be considered, as they provide insight into how jump performance is achieved in response to AEL.

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Accentuated eccentric loading; countermovement jump; youth athletes; Bayesian analysis

Introduction

Strength and conditioning (S&C) practitioners frequently integrate external load during ballistic jump training to enhance force production characteristics (Markovic et al., 2013; Mundy et al., 2017; Swinton et al., 2012), with the most common methods including a barbell positioned across the posterior aspect of the shoulders (Mundy et al., 2017), handheld dumbbells (Bordelon et al., 2022) or weighted vests attached to the torso (Harry

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et al., 2019). In youth athletes, this is generally limited to bodyweight only exercises, such as the countermovement jump (CMJ_{BW}) (Ramirez-Campillo et al., 2023). Although the precise reasons for this remain unclear, it is likely that alterations in landing mechanics (e.g., greater knee valgus and trunk flexion angle), particularly during periods of accelerated growth around peak height velocity (PHV), caution S&C practitioners against adding external load (Read et al., 2018). While the application of external load has been reported to increase CMJ_{BW} and squat jump performance in youth soccer players after a six-week training programme (Kobal et al., 2017), the concurrent reductions in propulsion phase velocity, rate of force development and jump height (Mundy et al., 2017) may be counterproductive in contexts where the aim is to maximise these variables (e.g., during dedicated speed training or phases of training near to competition). Therefore, alternative methods that can be used to enhance propulsion phase characteristics while promoting safe landing mechanics are likely of interest to S&C practitioners and warrant further investigation.

Submaximal accentuated eccentric loading (AEL; eccentric load above concentric load, but below concentric one-repetition maximum) can be used to enhance jump height and propulsion performance by increasing the rate or magnitude of eccentric muscle lengthening (Handford et al., 2021; Komi, 2000). This approach integrates an external load during the countermovement phase that is released prior to propulsion (Handford et al., 2021; Merrigan et al., 2022). Several mechanisms have been proposed to explain its potential effects. One of these mechanisms is that the increased eccentric loading amplifies elastic strain energy storage and return (Merrigan et al., 2022; Sheppard et al., 2007); however, recent findings do not clearly support this (Su et al., 2024). This mechanism also appears unlikely given that it depends on a rapid stretch-shortening cycle (SSC) with minimal movement time and lower-limb angular displacement (Anderson & Pandy, 1993), whereas the increased system mass experienced during AEL likely has the opposite effect. An alternative hypothesis is that AEL may alter neuromuscular activation to facilitate greater propulsive force and/or power output (Lloyd et al., 2022), yet Su et al. (2024) reported no clear differences in muscle activation during CMJ_{AEL} compared with CMJ_{BW}. Overall, evidence for the acute effects of AEL on jump height and force-time characteristics remains equivocal, with studies reporting both positive (Aboodarda et al., 2013; Lloyd et al., 2022; Sheppard et al., 2007) and negligible outcomes (Aboodarda et al., 2014; Bridgeman et al., 2016; Harrison et al., 2019; Moore et al., 2007; Su et al., 2024; Taber et al., 2023). Moreover, research examining its application within youth athlete populations remains limited.

To date, only one group of researchers has investigated AEL in youth athletes, using handheld dumbbells equivalent to 15% of body mass during a 0.3 m drop jump (Lloyd et al., 2022). Compared with the bodyweight drop jump condition, jump height was greater during AEL ($\Delta = 0.03$ m), accompanied by increases in both braking and propulsive impulse. Furthermore, spring-like correlation decreased and contact time increased, suggesting that AEL afforded more time to develop force, thereby enhancing take-off velocity (Bobbert & Van Zandwijk, 1999). Notably, the magnitude and timing of peak landing force did not differ significantly between conditions, indicating that AEL can be implemented without adverse mechanical consequences during landing (Lloyd et al., 2022). However, as AEL should be integrated with minimal disruption to overall movement mechanics (Wagle et al., 2017) and the drop jump is typically used to target fast SSC characteristics (Pedley et al., 2017), the aforementioned changes may represent an undesirable adaptation. Despite an acute increase in jump height, it is possible that participants were unable to tolerate the combined mechanical demands of AEL and the drop jump. This limited tolerance may stem from insufficient training experience or low relative strength, both of which are known to influence the ability to effectively manage eccentric braking during jumping in male and female youth athletes (Gillen et al., 2021). Consequently, implementing AEL in youth athletes may require simpler exercises, such as the CMJ, where technical demands are lower and eccentric loads can be more effectively managed.

The primary aim of this study was to investigate how handheld dumbbell load affects force-time characteristics during CMJ_{AEL} performed with loads equivalent to 20% and 30% of body mass (i.e., CMJ_{AEL20} and CMJ_{AEL30}). Recently published analytical techniques were employed to improve the accuracy of force-time data (Bright et al., 2024; Bright, Lake, Harry, et al., 2025). Specifically, because centre of mass (CoM) kinematics are derived from vertical ground reaction force (vGRF) under the assumption of a constant system mass, releasing an external load violates this and introduces error. To address this, separate forward and backward numerical integration procedures were applied (Bright et al., 2024; Bright, Lake, Harry, et al., 2025). Based on previous evidence, it was expected that CMJ_{AEL} would acutely enhance jump height and propulsion phase characteristics, particularly during CMJ_{AEL20}, while CMJ_{AEL30} would impose greater braking demands.

Material and methods

Participants

A sample of 19 adolescent participants (9 males and 10 females; age: 15 ± 2 years; stature: 1.66 ± 0.09 m; body mass: 54.8 ± 8.4 kg) volunteered to participate in this study. Biological maturity was estimated using the Khamis–Roche method (Khamis & Roche, 1994), with participants classified as circa-PHV (89–95%; n = 5) and post-PHV (> 95%; n = 14) (Meylan et al., 2014; Molinari et al., 2013; Ruf et al., 2022). Participants were free from injury and involved in regular sport training and physical education-based activity programmes, including S&C a minimum of one time per week. Written parental consent, participant assent and completion of a standardised physical activity readiness questionnaire were obtained before their participation. Ethical approval for the research was granted by the University Research Ethics Committee in accordance with the Declaration of Helsinki.

Testing procedures

Both sessions began with a 10 min standardised warm-up consisting of 5 min of stationary cycling, 10 bodyweight squats and lunges, and 3 submaximal to maximal effort CMJ_{BW}. Upon completion of the warm-up in session one, participants were familiarised with CMJ_{AEL}, which involved beginning the movement in an upright position whilst keeping their body and both dumbbells still. Upon the command '*3, 2, 1, jump!*', participants were instructed to *'perform the countermovement at your maximum comfortable speed, release the dumbbells as close to your lowest position as possible before moving upward and continue to jump as fast and as high as possible'* (Bright et al., 2024; Bright, Lake, Harry, et al., 2025). The emphasis on maximum comfortable speed was intended to encourage participants to descend quickly through the countermovement, but not at the decrement of movement technique. Participants completed between 4 and 6 trials to familiarise with CMJ_{AEL} (mean ± standard deviation (SD) = 5 ± 1), during which self-selected dumbbell loads between 20% and 30% of body mass were used. After releasing the dumbbells, participants were instructed to return their arms to an akimbo position for the remainder of the jump and landing. Standardised trainers were worn during all testing sessions to control for any potential influence of footwear on force—time characteristics (Heishman et al., 2021).

For the data collection session, participants were advised to arrive at the biomechanics laboratory in a hydrated state, between two and four hours postprandial, and to avoid vigorous exercise for at least 48 hours prior to testing. After the warm-up, participants performed up to three CMJ_{AEL} trials increasing from 80 to 100% of perceived effort to refamiliarise themselves with the movement. Participants then completed three trials of CMJ_{BW} both pre and post each of the following CMJ_{AEL} conditions that were performed in a randomised, counterbalanced order: a) three trials of CMJ_{AEL20} and b) three trials of CMJ_{AEL30}. One minute of rest was provided between trials, and approximately three minutes was allocated between conditions.

The CMJ_{AEL} loads employed in this study were selected based on a number of considerations. First, previous CMJ_{AEL} research using handheld dumbbells has applied loads ranging from 20% (Harrison et al., 2019; Sheppard et al., 2007) to 40% of body mass (Godwin et al., 2021) in males, and approximately 15% of body mass in females (Harrison et al., 2019). These studies generally reported positive outcomes, although Harrison et al. (Harrison et al., 2019) advised against the use of CMJ_{AEL} due to observed reductions in propulsion phase performance and disruptions to natural movement mechanics. However, concerns have been raised regarding the analytical procedures, which may have underestimated propulsion phase characteristics (Bright et al., 2024; Bright, Lake, Harry, et al., 2025). Second, Merrigan et al. (Merrigan et al., 2022) recommended beginning with a load equivalent to 20% of body mass for individuals with limited S&C experience and AEL familiarity, which was applicable to the current cohort. Finally, pilot testing indicated that loads between 20% and 30% of body mass resulted in the largest acute improvement in jump height. Accordingly, 20% and 30% of body mass were selected as appropriate and effective AEL magnitudes for this investigation.

Data acquisition and analysis

Data from all trials were captured using two portable force platforms positioned parallel to one another (Kistler Type 9286B, Kistler Instruments, Hampshire, United Kingdom), sampling at 1000 Hz. Signals were exported to MATLAB for analysis (R2022b; The Mathworks, Inc., Natick, MA, USA). Raw vGRF signals from each force platform were summed to represent the vGRF acting at the system CoM: body only during CMJ_{BW} and body plus dumbbells during CMJ_{AEL}. The summed vGRF signals were filtered using a fourth-order, bidirectional, low-pass Butterworth digital filter with a cut-off frequency of 50 Hz. The cut-off frequency was selected based on recent recommendations (Harry et al., 2022) and a residual analysis whereby a range of low-pass filter cut-off frequencies were applied and the residuals were plotted to determine the point where further increases in cut-off frequency did not significantly reduce the noise (Winter, 2009). The vGRF signal was filtered after time points of interest (described later) were identified to ensure that it did not affect their location.

For CMJ_{AEL} conditions, this study employed forward and backward numerical integration to account for transient changes in system mass. This enables the accurate calculation of velocity and displacement, which are critical for reliably quantifying force-time characteristics (Bright et al., 2024; Bright, Lake, Harry, et al., 2025). These methods are detailed below.

Forward numerical integration

System weight, representing bodyweight + dumbbell weight (CMJ_{AEL}) or bodyweight only (CMJ_{BW}), was determined by averaging one second of the vGRF signal at the start of the jump as the participants stood upright and still (i.e., weighing period). Movement onset was defined using a threshold of bodyweight ±5*SD of the vGRF calculated during the weighing period (McMahon et al., 2018; Owen et al., 2014). To ensure CoM velocity and displacement were effectively zero at movement onset for valid numerical integration (Street et al., 2001), a 30 ms backward offset was applied from the point of threshold crossing (Owen et al., 2014). Net vGRF (vGRF—system weight) was divided by system mass to calculate acceleration according to Newton's Second Law of Motion. Acceleration was then integrated using the trapezoidal rule (MATLABs '*cumtrapz*' function) to obtain velocity, and again to calculate displacement (Owen et al., 2014).

Backward numerical integration

For CMJ_{AEL} conditions, the vGRF signal was flipped using MATLABs '*flipud*' function such that the first recorded data point became the last data point in the time-history. System weight (bodyweight only, following dumbbells' release) was subsequently calculated from a one second post-landing period where participants were instructed to return to an upright and still position as quickly as possible (Bright et al., 2024; Bright, Lake, Harry, et al., 2025). This period ensured near-zero initial velocity and displacement and was used to calculate the mean and SD of the vGRF signal. The identification of movement onset was repeated according to the procedures detailed above. Acceleration, velocity and displacement were then calculated using the same procedures as in forward integration (Bright, Lake, Harry, et al., 2025). The resulting data were flipped to match the original direction of the vGRF signal.

Phase and dumbbell release identification

The start of the braking phase was defined as the instant when vGRF returned to system weight, corresponding to the frame at which peak negative velocity occurs (McMahon et al., 2018). This method was applied to both CMJ_{BW} and CMJ_{AEL} conditions; however, in CMJ_{AEL}, dumbbell release timing could affect whether system weight or bodyweight was referenced (Bright et al., 2024; Bright, Lake, Harry, et al., 2025). Specifically, if the dumbbells were released during the unweighting phase, the start of this phase was identified as the point at which vGRF returned to bodyweight. Conversely, if the dumbbells were released after the unweighting phase, the point at which vGRF returned to system weight was used (Bright et al., 2024; Bright, Lake, Harry, et al., 2025). The end of the braking phase was then identified when velocity returned to zero, marking the lowest point of the countermovement (Linthorne, 2021). In all CMJ_{AEL} trials, the dumbbells' release occurred before the end of the braking phase; therefore, this point was identified using backward integrated velocity (Bright et al., 2024; Bright, Lake, Harry, et al., 2025). The start of the propulsion phase is typically determined as the instant that velocity is positive (Kibele, 1998; Linthorne, 2021); however, a velocity threshold of 0.01 $m{\cdot}s^{-1}$ was used in line with recommendations (McMahon et al., 2018; McMahon, Murphy, et al., 2017; McMahon, Rej, et al., 2017). Take-off and landing, with the former marking the end of the propulsion phase, were identified using a threshold equal to 10 N based upon analyses of the residual vGRF during which the force platforms were unloaded.

The difference between forward integration and backward integration signals was calculated, and the first instance at which the difference equalled zero (i.e., signal intersection point) was used to identify the point in which the dumbbells were released (Bright et al., 2024; Bright, Lake, Harry, et al., 2025). This was chosen as it represents the instant at which the two masses (e.g., system mass with and without dumbbells) became equal as they transitioned to take each other's magnitude. Net vGRF and CoM acceleration, velocity and displacement data for CMJ_{AEL} conditions were then combined using forward and backward integration prior to and after the dumbbell release point, respectively. This process was essential due to the changes in system weight that compromise the integration accuracy after the dumbbells' release.

An overview of the variables calculated from vGRF data, along with their units and definitions, is provided in Table 1.

Statistical analyses

To assess the reliability of dependent variables, intraclass correlation coefficient (ICC) and coefficient of variation (CV) were computed for all experimental conditions (CMJ_{BW}, CMJ_{AEL20}, CMJ_{AEL30}). All analyses were performed in R studio using the BRMS package (Bürkner, 2018). For each dependent variable within each condition, a Bayesian random-intercept model with participant as a random effect was fitted. Posterior distributions were obtained using four chains of 4000 iterations each. From the posterior samples, ICCs were computed as:

$$ICC = \frac{\sigma^2\text{between}}{\sigma^2\text{between} + \sigma^2\text{within}}$$

where $\sigma^2_{\text{between}}$ represents the variance between participants (random intercept variance) and σ^2_{within} represents the residual variance. Similarly, CVs were calculated for each posterior draw as:

$$CV = \frac{\sigma_{\text{residual}}}{\text{mean}}$$

Table 1. Variable definitions.

Variable	Definition
Jump Height (m)	Calculated using the velocity at take-off squared, divided by the constant acceleration of gravity (9.81 $m \cdot s^{-2}$) multiplied by 2.
RSI_{mod} (AU)	Jump height divided by time to take-off.
Time to Take-Off (s)	Time from movement onset to first vGRF value below 10 N.
Countermovement Depth (m)	Vertical displacement of the CoM from movement onset to its lowest point during the countermovement phase.
vGRF at Zero Velocity (N/kg)	vGRF at countermovement depth, normalised to body mass.
Unweighting Time (s)	Time from movement onset to peak negative velocity.
Braking Time (s)	Time from peak negative velocity to countermovement depth.
Propulsion Time (s)	Time from countermovement depth to first vGRF value below 10 N.
Braking Mean vGRF (N/kg)	Mean vGRF during the braking phase, from peak negative velocity to countermovement depth, normalised to body mass.
Propulsion Mean vGRF (N/kg)	Mean vGRF during propulsion phase, from countermovement depth to first vGRF value below 10 N, normalised to body mass.
Unweighting Peak Velocity ($m \cdot s^{-1}$)	Peak negative velocity during the unweighting phase.
Braking Mean Velocity ($m \cdot s^{-1}$)	Mean velocity during the braking phase, from peak negative velocity to countermovement depth.
Propulsion Mean Velocity ($m \cdot s^{-1}$)	Mean velocity during the propulsion phase, from countermovement depth to first vGRF value below 10 N.
Braking Mean Power (W/kg)	Mean value of the product of vGRF and velocity signals from peak negative velocity to 0 $m \cdot s^{-1}$ velocity, normalised to body mass.
Propulsion Mean Power (W/kg)	Mean value of the product of vGRF and velocity signals from 0 $m \cdot s^{-1}$ velocity to first vGRF value below 10 N, normalised to body mass.

Abbreviations: m, metres; N, Newton's; kg, kilogram; s, seconds; W, Watts; RSI_{mod}, reactive strength index modified; AU, arbitrary units; CoM, centre of mass; vGRF, vertical ground reaction force; SW, system weight.

Posterior ICCs and CVs were summarised as their mean and 95% credible intervals for each dependent variable × condition combination, and CVs were expressed as percentage values. This approach provides a Bayesian estimate of relative and absolute reliability, accounting for both between-subject differences and uncertainty in parameter estimates. ICCs were classified as poor (≤0.49), moderate (0.50 to 0.74), good (0.75 to 0.89) and excellent (≥0.90) according to the interpretation thresholds proposed by Koo and Li (Koo & Li, 2016), while uncertainty in the present study was quantified using the lower bound of the 95% credible interval (CI_{95}). The CV estimates were expressed as a percentage, with values of <5%, 5 to 10%, >10 to 15% and >15% (based on the upper CI_{95}) considered to represent excellent, good, moderate and poor reliability, respectively.

To examine the effects of handheld dumbbell load on force-time characteristics, Bayesian multilevel models were conducted in the brms package (Bürkner, 2018), which implements Hamiltonian Markov Chain Monte Carlo sampling with a No-U-Turn Sampler via Stan. Default settings were used for chains, iterations, thinning, and burn-in, except for the model estimating propulsive mean vGRF, which required 4000 iterations to achieve convergence. Convergence of all models was verified by R values equal to 1. Bayesian multilevel models were fitted, allowing individual intercepts to vary, with either Gaussian or skew-normal response distributions. Following this, data were inspected using posterior predictive checks (Gabry & Mahr, 2025), and model performance was compared using Leave-One-Out cross-validation (LOO) to assess out-of-sample predictive accuracy based on the expected log predictive density (Vehtari et al., 2017), with the final model selected based on both the best LOO score and visual inspection of the posterior distributions.

Estimated marginal means were derived from the best-fitting models using *emmeans* (Lenth, 2020), with pairwise contrasts reported alongside their 95% Highest Density Intervals (HDI_{95}). Posterior probabilities were calculated for (a) change above/below zero (probability of direction) and (b) change exceeding the coefficient of variation (CV; practical significance), using the *bayestest R* package (Makowski et al., 2019). The CV was determined for each participant (SD ÷ mean) within each condition, and the mean value across all conditions was used as the final CV threshold.

Bayesian multilevel models included condition, sex, and their interaction as fixed effects. Condition (CMJ_{BW}, CMJ_{AEL20}, CMJ_{AEL30}) was treated as a within-subject factor and sex (male, female) as a between-subject factor. This design enabled evaluation of potential sex-based differences in response to loading, while the primary focus remained on the overall effects of condition.

Results

The ICC and CV% reliability data for all dependent variables across experimental conditions are provided in Figure 1 and Figure 2, respectively.

Estimated marginal means and associated HDI_{95} for each variable and condition are presented in Table 2. Although sex was included in the initial models, no meaningful sex × condition interactions were identified, with posterior contrasts indicating nearly identical loading responses between males and females. Accordingly, the results below combine data from both sexes to focus on the overall effects of condition.

Jump height was highest in the CMJ_{AEL20} and CMJ_{AEL30} and lowest in CMJ_{BW} (Table 3; Figure 3). While the difference between CMJ_{AEL20} and CMJ_{AEL30} was uncertain, both conditions suggest a 100% probability of improving jump height compared to CMJ_{BW}. RSI_{mod} exhibited small and uncertain changes across conditions, although CMJ_{AEL20} appeared slightly higher than CMJ_{BW}, whereas CMJ_{AEL30} was slightly lower. Time to take-off increased in both loaded conditions, with the biggest change in CMJ_{AEL30}. The difference between CMJ_{AEL20} and CMJ_{AEL30} was small and unlikely to be practically relevant. When comparing both AEL conditions to CMJ_{BW}, countermovement depth showed increased uncertainty, with overlapping posterior distributions and less than 10% chance that the change exceeded the CV (Table 3).

The vGRF at zero velocity was higher in CMJ_{AEL20} compared with CMJ_{BW}, whereas differences between CMJ_{AEL30} and CMJ_{BW} were uncertain. Unweighting time increased progressively across conditions, with CMJ_{AEL30} showing the largest change. The difference between CMJ_{AEL20} and CMJ_{AEL30} was small and unlikely to be practically relevant. Braking time was increased in CMJ_{AEL30} compared with CMJ_{BW} (Table 4). Propulsion time also increased in both loaded conditions relative to CMJ_{BW} (Table 4). Both CMJ_{AEL20} and CMJ_{AEL30} produced meaningful reductions in unweighting peak velocity compared with CMJ_{BW}. CMJ_{AEL20} also showed a meaningful increase relative to CMJ_{AEL30}. Braking mean velocity differences were modest and uncertain across conditions, with a slight decrease observed from CMJ_{AEL20} to CMJ_{AEL30}. Propulsion mean velocity was greater during both CMJ_{AEL20} and CMJ_{AEL30} compared with CMJ_{BW}, with the increase more certain for CMJ_{AEL20}.

Braking mean vGRF was higher in CMJ_{AEL20} and CMJ_{AEL30} compared with CMJ_{BW}; however, only the difference between CMJ_{AEL20} and CMJ_{BW} exceeded the

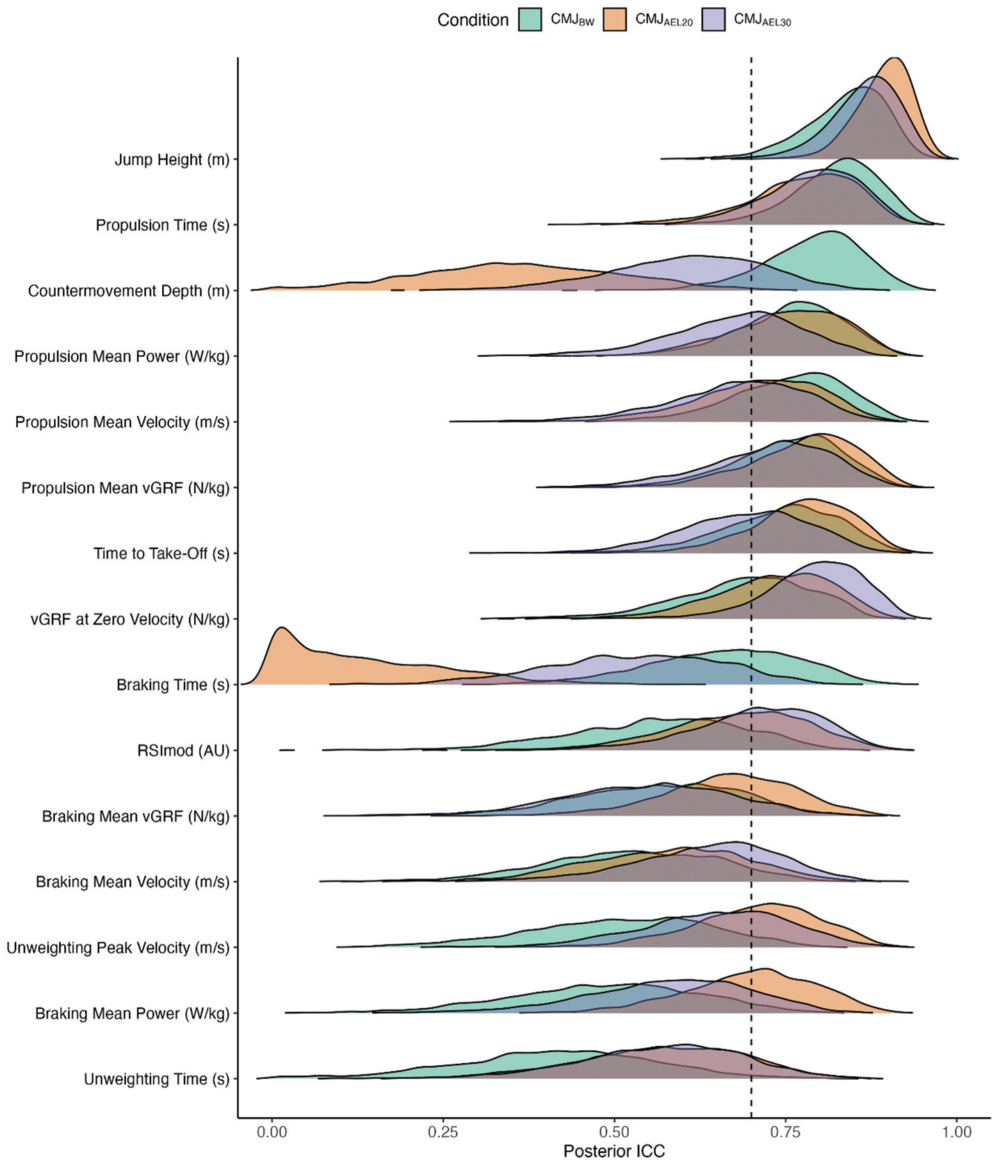

Figure 1. Posterior density distributions of ICCs for each dependent variable across conditions (CMJ_{BW}, CMJ_{AEL20} and CMJ_{AEL30}). The dashed vertical line is included as a reference point to facilitate comparison across variables and conditions. Wider distributions indicate greater uncertainty in the posterior estimates.

CV with practical certainty. Propulsion mean vGRF was lower in both CMJ_{AEL20} and CMJ_{AEL30} relative to CMJ_{BW} (Table 5), with near 100% probability of a negative effect in both cases. There was also a possibility that mean power increased in CMJ_{AEL20} relative to CMJ_{BW}, although uncertainty increased when considering the CV. CMJ_{AEL20} possibly increased propulsive mean power, with

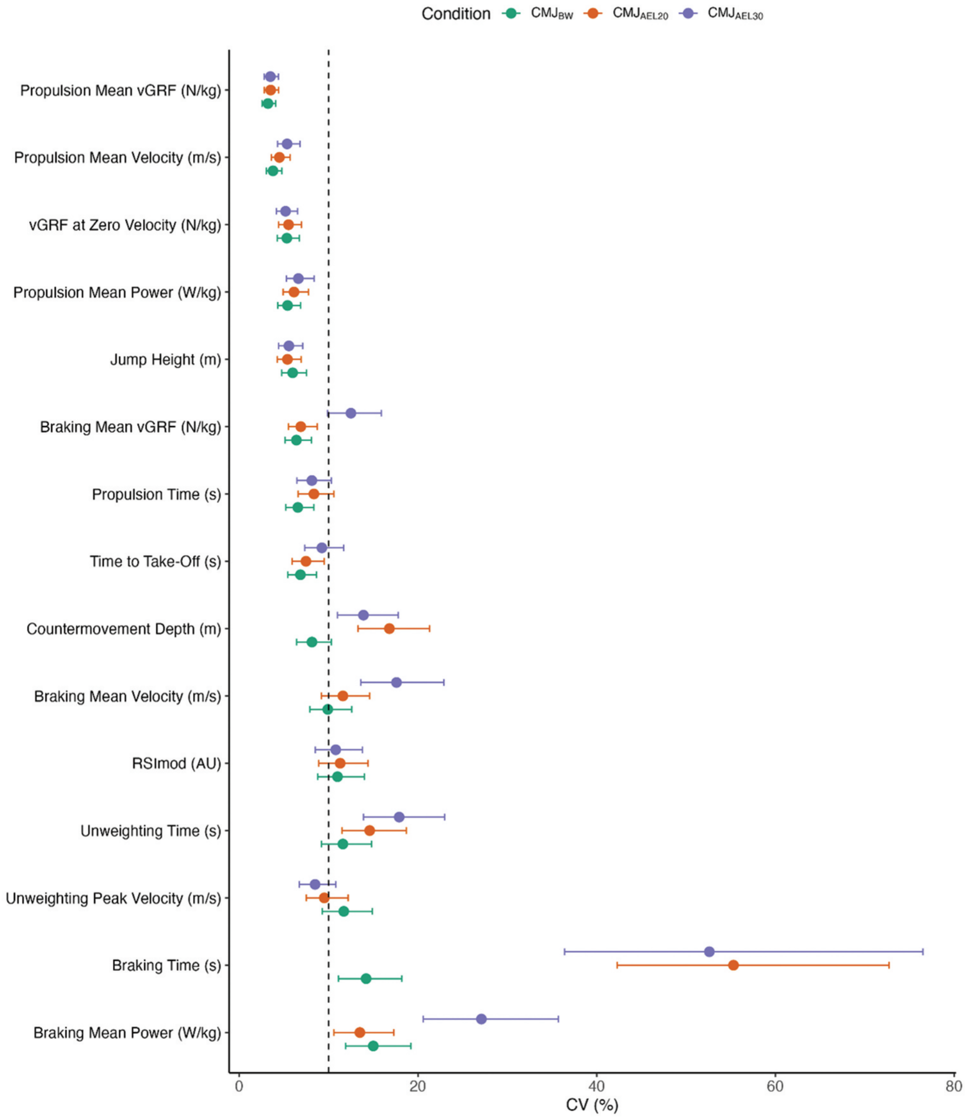

Figure 2. Posterior estimates of the CV% for each dependent variable across conditions (CMJ_{BW}, CMJ_{AEL20} and CMJ_{AEL30}). Points represent posterior means, and horizontal lines denote CI_{95}. The dashed vertical line is provided as a reference to aid visual comparison across variables and conditions.

a potentially practically meaningful difference; however, all other comparisons were highly uncertain (Table 5).

Discussion and implication

The primary aim of this study was to examine the effects of handheld dumbbell load on force-time characteristics during CMJ_{AEL}. Posterior estimates indicated that jump height was highest in CMJ_{AEL20} and CMJ_{AEL30} and lowest in CMJ_{BW}, and there was a 100%

Table 2. Estimated marginal means and HDI_{95} for all variables by condition.

	CMJ_{BW}		CMJ_{AEL20}		CMJ_{AEL30}	
Variable	Estimate	HDI_{95}	Estimate	HDI_{95}	Estimate	HDI_{95}
Jump Height (m)	0.233	0.214, 0.251	0.257	0.240, 0.276	0.255	0.237, 0.274
RSI_{mod} (AU)	0.261	0.243, 0.280	0.269	0.251, 0.288	0.252	0.233, 0.270
Time to Take-Off (s)	0.893	0.833, 0.952	0.968	0.908, 1.029	1.030	0.969, 1.091
Countermovement Depth (m)	−0.304	−0.329, −0.281	−0.316	−0.339, −0.293	−0.312	−0.336, −0.289
vGRF at Zero Velocity (N/kg)	18.2	17.5, 19.0	18.9	18.1, 19.6	18.5	17.7, 19.2
Unweighting Time (s)	0.373	0.337, 0.408	0.455	0.422, 0.492	0.522	0.486, 0.556
Braking Time (s)	0.216	0.359, 0.478	0.215	0.151, 0.272	0.418	0.359, 0.478
Propulsion Time (s)	0.306	0.283, 0.328	0.334	0.311, 0.357	0.341	0.319, 0.364
Braking Mean vGRF (N/kg)	14.2	13.5, 14.9	15.5	14.7, 16.1	15.2	14.5, 15.9
Propulsion Mean vGRF (N/kg)	16.9	16.4, 17.4	16.6	16.1, 17.1	16.4	15.9, 16.8
Unweighting Peak Velocity ($m·s^{-1}$)	−0.95	−1.00, −0.88	−1.07	−1.13, −1.00	−1.22	−1.28, −1.16
Braking Mean Velocity ($m·s^{-1}$)	−0.62	−0.67, −0.58	−0.65	−0.70, −0.60	−0.61	−0.66, −0.56
Propulsion Mean Velocity ($m·s^{-1}$)	1.24	1.20, 1.28	1.29	1.25, 1.33	1.27	1.23, 1.31
Braking Mean Power (W/kg)	8.34	7.38, 9.33	9.58	8.64, 10.58	8.77	7.76, 9.74
Propulsion Mean Power (W/kg)	19.6	18.7, 20.5	20.2	19.4, 21.1	19.7	18.8, 20.6

Abbreviations: CMJ_{BW}, bodyweight countermovement jump; CMJ_{AEL20}, countermovement jump with handheld dumbbells at 20% of body mass; CMJ_{AEL30}, countermovement jump with handheld dumbbells at 30% of body mass; HDI_{95}, 95% highest density intervals; m, metres; RSI_{mod}, reactive strength index modified; AU, arbitrary units; N, Newtons; kg, kilograms; s, seconds; W, Watts.

Table 3. Pairwise Bayesian contrasts for jump height, RSI_{mod}, time to take-off, countermovement depth and vGRF at zero velocity.

Variable	Output	CMJ_{AEL20}-CMJ_{BW}	CMJ_{AEL30}-CMJ_{BW}	CMJ_{AEL20}-CMJ_{AEL30}
Jump Height (m)	Estimate	0.025	0.022	0.003
	HDI_{95}	0.019, 0.030	0.017, 0.028	−0.003, 0.008
	$P > 0$	100	100	81.92
	$P > CV$	100	100	0.19
RSI_{mod} (AU)	Estimate	0.008	−0.009	0.017
	HDI_{95}	−0.004, 0.019	−0.020, 0.003	0.006, 0.028
	$P > 0$	91.65	93.75	99.95
	$P > CV$	0.58	0.85	16.00
Time to Take-Off (s)	Estimate	0.074	0.137	−0.062
	HDI_{95}	0.040, 0.1081	0.104, 0.169	−0.098, −0.032
	$P > 0$	100	100	99.98
	$P > CV$	0.03	38.00	0.00
Countermovement Depth (m)	Estimate	−0.012	−0.008	−0.003
	HDI_{95}	−0.026, 0.005	−0.024, 0.006	−0.017, 0.012
	$P > 0$	93.40	86.20	65.20
	$P > CV$	9.00	4.00	0.68
vGRF at Zero Velocity (N/kg)	Estimate	0.637	0.236	0.402
	HDI_{95}	0.218, 1.002	−0.147, 0.633	0.004, 0.795
	$P > 0$	99.98	88.78	97.62
	$P > CV$	18.00	0.10	2.00

Abbreviations: CMJ_{BW}, bodyweight countermovement jump; CMJ_{AEL20}, countermovement jump with handheld dumbbells at 20% of body mass; CMJ_{AEL30}, countermovement jump with handheld dumbbells at 30% of body mass; HDI_{95}, 95% highest density intervals; $p > 0$, probability the effect is positive; $p > CV$, probability the effect exceeds measurement error; m, metres; RSI_{mod}, reactive strength index modified; AU, arbitrary units; N, Newtons; kg, kilograms.

probability that AEL conditions increased jump height relative to CMJ_{BW} (Tables 2 and 3; Figure 3). There was also a 100% posterior probability that these differences exceeded the CV, providing strong evidence that the observed effects likely represent true changes and that similar differences may be expected in future observations. However, CMJ_{AEL20} and CMJ_{AEL30} could not be distinguished from each other, as less than 1% of the

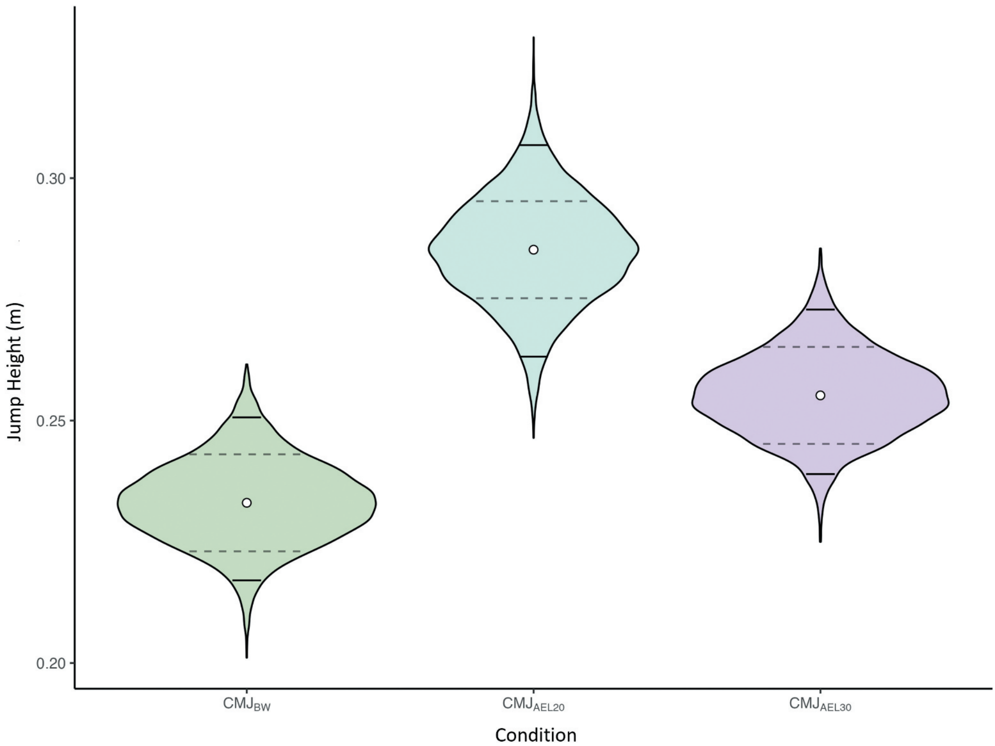

Figure 3. Jump height across CMJ_{BW}, CMJ_{AEL20} and CMJ_{AEL30}. Distributions represent posterior estimates from the Bayesian model. White dots denote the posterior mean; dashed black lines indicate the CV, and solid black lines represent the HDI_{95}. Violin widths reflect the relative density of posterior samples.

posterior distribution fell beyond the CV. Despite time to take-off increasing under both AEL conditions, the highest RSI_{mod} was observed in CMJ_{AEL20}, and this can be explained by the improvement in jump height offsetting the longer time to take-off. Collectively, these results suggest that CMJ_{AEL} acutely increases jump height, likely through a prolonged time to take-off that facilitates greater opportunity for force production, though phase-specific analyses are required to clarify the mechanical adaptations underpinning these effects.

Implementing AEL through handheld dumbbells has been shown to acutely improve jump height (Aboodarda et al., 2013; Sheppard et al., 2007), although some researchers have reported little or no change (Godwin et al., 2021; Harrison et al., 2019; Taber et al., 2023). This can be explained by Newton's Second Law of Motion, where jump height depends on the net impulse generated during propulsion, which can be increased through a greater magnitude of force, a longer duration of force application, or both, assuming system mass remains constant (Linthorne, 2021). In this study, increases in jump height during CMJ_{AEL} were accompanied by clear changes in propulsion phase characteristics. Notably, propulsion time increased in both CMJ_{AEL20} and CMJ_{AEL30}, with a strong chance of these changes exceeding the CV (97% and 100%, respectively). Although propulsion mean vGRF decreased, the longer propulsion time likely enabled

Table 4. Pairwise Bayesian contrasts for unweighting, braking and propulsion phase durations and mean velocities, alongside eccentric momentum.

Variable	Output	CMJ_{AEL20}-CMJ_{BW}	CMJ_{AEL30}-CMJ_{BW}	CMJ_{AEL20}-CMJ_{AEL30}
Unweighting Time (s)	Estimate	0.081	0.149	−0.067
	HDI_{95}	0.050, 0.113	0.118, 0.179	−0.098, −0.038
	P > 0	100	100	100
	P > CV	18.00	100	3.00
Braking Time (s)	Estimate	0.000	0.203	−0.203
	HDI_{95}	−0.057, 0.060	0.139, 0.262	−0.265, −0.143
	P > 0	50.25	100	100
	P > CV	0.02	100	100
Propulsion Time (s)	Estimate	0.029	0.035	−0.007
	HDI_{95}	0.019, 0.038	0.026, 0.045	−0.017, 0.002
	P > 0	100	100	92.50
	P > CV	97.00	100	0.60
Unweighting Peak Velocity ($m{\cdot}s^{-1}$)	Estimate	−0.126	−0.273	0.146
	HDI_{95}	−0.167, −0.078	−0.316, −0.229	0.101, 0.190
	P > 0	100	100	100
	P > CV	21.00	4.00	100
Braking Mean Velocity ($m{\cdot}s^{-1}$)	Estimate	−0.027	0.013	−0.039
	HDI_{95}	−0.063, 0.009	−0.023, 0.048	−0.075, −0.002
	P > 0	92.10	74.58	97.97
	P > CV	0.98	0.13	5.00
Propulsion Mean Velocity ($m{\cdot}s^{-1}$)	Estimate	0.051	0.028	0.023
	HDI_{95}	0.030, 0.073	0.007, 0.050	0.002, 0.045
	P > 0	100	99.22	97.82
	P > CV	66.00	6.00	1.00

Abbreviations: CMJ_{BW}, bodyweight countermovement jump; CMJ_{AEL20}, countermovement jump with handheld dumbbells at 20% of body mass; CMJ_{AEL30}, countermovement jump with handheld dumbbells at 30% of body mass; HDI_{95}, 95% highest density intervals; $p > 0$, probability the effect is positive; $p > CV$, probability the effect exceeds measurement error; s, seconds; m, metres.

Table 5. Pairwise Bayesian contrasts for mean braking and propulsion vGRF and power.

Variable	Output	CMJ_{AEL20}-CMJ_{BW}	CMJ_{AEL30}-CMJ_{BW}	CMJ_{AEL20}-CMJ_{AEL30}
Braking Mean vGRF (N/kg)	Estimate	1.312	1.039	0.269
	HDI_{95}	0.848, 1.81	0.479, 1.57	−0.292, 0.82
	P > 0	100	99.98	84.67
	P > CV	90.00	55.00	1.00
Propulsion Mean vGRF (N/kg)	Estimate	−0.296	−0.513	0.219
	HDI_{95}	−0.511, −0.083	−0.732, −0.303	0.005, 0.441
	P > 0	99.64	100	97.47
	P > CV	9.00	74.00	2.00
Braking Mean Power (W/kg)	Estimate	1.236	0.428	0.807
	HDI_{95}	0.541, 1.97	−0.230, 1.13	0.114, 1.50
	P > 0	99.98	89.05	98.80
	P > CV	0.15	27.00	4.00
Propulsion Mean Power (W/kg)	Estimate	0.665	0.162	0.507
	HDI_{95}	0.211, 1.125	−0.294, 0.636	0.030, 0.969
	P > 0	99.75	75.80	98.25
	P > CV	13.00	0.08	3.00

Abbreviations: CMJ_{BW}, bodyweight countermovement jump; CMJ_{AEL20}, countermovement jump with handheld dumbbells at 20% of body mass; CMJ_{AEL30}, countermovement jump with handheld dumbbells at 30% of body mass; HDI_{95}, 95% highest density intervals; $p > 0$, probability the effect is positive; $p > CV$, probability the effect exceeds measurement error; N, Newtons; W, Watts.

participants to apply force over a greater period of time, thereby increasing net impulse and in turn explaining the increase in jump height observed (Bobbert & Van Zandwijk, 1999). Changes in propulsion mean velocity suggest a possible increase under both CMJ_{AEL} conditions; however, these effects were uncertain, particularly for CMJ_{AEL30}

($p > \mathrm{CV} = 66\%$ and 6%, respectively). Similarly, differences in propulsion mean power between conditions were mostly uncertain, though a possible increase was evident between CMJ_{BW} and CMJ_{AEL20}. Given that changes in countermovement depth were also uncertain, the increase in propulsion mean power in CMJ_{AEL20} likely resulted from the concurrent rise in propulsion mean velocity (Samozino et al., 2012), rather than from a greater range of motion or force. Nonetheless, future research should examine propulsion displacement to determine whether CMJ_{AEL} leads to a more extended take-off position, which may help to explain the propulsion phase changes observed in this study (Pommerell et al., 2024). Furthermore, it is important to acknowledge that these findings represent acute responses and may not reflect long-term adaptations.

A key consideration when implementing CMJ_{AEL} is the manner in which external load is applied to the system. Under constrained conditions (i.e., controlled squat depth, trunk and arm motion), Su et al. (Su et al., 2024) recently found no consistent evidence of improved propulsion phase performance during CMJ_{AEL} at 10%, 20% and 30% of body mass relative to CMJ_{BW}. In constraining the movement, it was concluded that participants experienced a reduced contribution from the trunk and hip extensors (Su et al., 2024). In contrast, the current study imposed only a partial constraint, limiting arm swing due to the use of handheld dumbbells before placing hands on hips, while allowing participants to otherwise perform the jump using their preferred strategy. Although countermovement depth did not change across conditions, the increase in propulsion time and reduction in vGRF suggest that force was applied over a longer duration. Despite this reduction in mean vGRF, propulsion mean velocity increased at CMJ_{AEL20}, which may reflect an altered strategy rather than a mechanical effect. For example, adding handheld dumbbells to the system may have encouraged a strategy in which participants leaned forward and relied more on the hip extensors, possibly due to a reduced ability to attenuate and produce force through the knee extensors with external load (Lees et al., 2004; Vanezis & Lees, 2005). Although speculative, as this was not directly assessed in the current study, such a strategy could reflect insufficient muscular strength to effectively cope with CMJ_{AEL}. Alternatively, while knee and ankle joint contributions are important to CMJ_{BW} performance (McErlain-Naylor et al., 2014), our findings may suggest that when the trunk and arms are loaded with handheld dumbbells, athletes may naturally shift the demand to the hip joint. However, future research employing CMJ_{AEL} joint level analyses is required to confirm this interpretation.

Regardless of the impact on outcome variables such as jump height and RSI_{mod}, CMJ_{AEL} could be incorporated in S&C programmes to specifically target changes in an athletes' braking capacity and ability to apply a sufficient impulse during tasks such as landing, deceleration and change of direction (Harper et al., 2022, 2024). From a mechanical standpoint, an increase in unweighting peak negative velocity would elevate the mechanical demand experienced during braking (McMahon et al., 2018). This pattern was evident from CMJ_{BW} to both loading conditions, although distinct differences emerged between CMJ_{AEL20} and CMJ_{AEL30}. During CMJ_{AEL20}, participants maintained a similar braking phase duration while increasing mean vGRF, velocity and power, suggesting that this load enhanced participants ability to decelerate within a comparable timeframe to CMJ_{BW}. In contrast, CMJ_{AEL30} was characterised by a certain increase in braking time accompanied by reductions in mean vGRF and velocity, leading to a decrease in mean power. This suggests that the higher load slowed the braking phase and reduced the capacity to rapidly attenuate force. Although vGRF at zero velocity was greatest during CMJ_{AEL20}, differences across conditions remained uncertain, consistent with recent findings (Su et al., 2024). However, it is worth noting that braking time demonstrated the lowest reliability across CMJ_{AEL} conditions (Figure 1 and 2). This may be explained by inconsistencies in the timing of dumbbell release (Bright, Lake, Handford, et al., 2025). For example, releasing the dumbbells earlier reduces system mass and braking demand, potentially shortening braking duration, whereas retaining them for longer increases system mass, requiring a greater impulse to decelerate and thereby extending the braking phase. Ultimately, these results should therefore be interpreted with caution, and CMJ_{AEL} should be implemented progressively to allow athletes to habituate to the loading demands (Bright, Lake, Handford, et al., 2025). It should also be reiterated that these findings reflect acute responses, and longitudinal research is required to determine the adaptations that occur over time in youth athlete populations.

When interpreting the findings of this study, several limitations should be acknowledged. First, handheld dumbbells at 20% and 30% of body mass were examined; therefore, it is unclear whether different equipment and loads would have a different effect on force-time characteristics when analysed using the approach employed here. Moreover, because loads were prescribed relative to body mass rather than individual strength, participants with differing strength capacities may have experienced distinct mechanical or neuromuscular demands under the same relative loading conditions. Second, we only reported force-time characteristics; the addition of 3-dimensional motion capture would facilitate a more detailed understanding of CMJ_{AEL}. In particular, quantifying CMJ_{AEL} induced alterations in joint level kinematics and kinetics (e.g., angular displacement, velocity, moments, and relative joint contributions such as hip versus knee dominant strategies) could reveal compensatory mechanisms that inform more targeted S&C prescription. Third, although minimal sex-based differences were observed, participants were not matched for relative strength, meaning any apparent sex effects may have been confounded by interindividual variation in strength levels (Comfort et al., 2024; Nimphius et al., 2019). Future studies should therefore measure relative strength and either match participants or adjust statistically (e.g., via covariates or normalisation) when comparing sexes. Additionally, given that CMJ_{AEL} is intended to facilitate greater braking vGRF, it would be valuable to determine whether stronger individuals or those with greater training experience derive greater benefit from this technique. Finally, while the present findings reflect acute responses, future research should examine the chronic adaptations to CMJ_{AEL} exposure in youth athletes and its progression within S&C programmes. Longitudinal studies could also assess whether handheld dumbbell CMJ_{AEL} serves as an effective precursor to more advanced methods, such as drop jumps with AEL. Despite these limitations, the current study provides novel and practically relevant insights into the potential application of CMJ_{AEL} in youth athletes.

Conclusion

This study is the first to investigate the effects of progressive handheld dumbbell loads on force-time characteristics during CMJ_{AEL} in youth athletes. Compared with CMJ_{BW}, jump height was greater in CMJ_{AEL} conditions, likely due to modifications in countermovement strategy and increased propulsion phase time and mean velocity. In contrast, braking responses were less consistent: although braking vGRF tended to increase under load, these changes were not accompanied by meaningful improvements in braking velocity or power, particularly at higher loading. Collectively, these findings indicate that CMJ_{AEL} can acutely enhance select force-time characteristics; however, its effects are both load and phase dependent. Accordingly, S&C practitioners should implement CMJ_{AEL} judiciously in youth physical development programmes, tailoring load magnitude to training experience and the specific mechanical outcomes targeted within a given training phase. For example, if the goal is to acutely enhance jump height, both CMJ_{AEL} conditions may be implemented; however, when the aim is to introduce external load without increasing braking time, CMJ_{AEL20} appears the more appropriate option. Nevertheless, future research is warranted to determine whether specific coaching cues can help reduce unwanted changes in phase durations without compromising jump height.

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