EFFECTS OF ADDITIONAL LOAD ON LOWER LIMB JOINT WORK AND THE RATIO BETWEEN THE BRAKING AND PROPULSION COUNTERMOVEMENT JUMP PHASE

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The purpose of this study was to identify the effect of additional load on lower limb joint work and joint work ratio between the braking and propulsion countermovement jump (CMJ) phase. Thirteen male sport students performed CMJ with five different loads up to 80% of body mass. Total joint work was significantly affected by the additional load and CMJ phase. A significant interaction effect of additional load and CMJ phase was found for ankle and knee joint work. Joint work ratio was significantly affected by load in the knee and hip joint. The braking proportion of the total joint work increased as additional load increased. The alterations in joint work and joint work ratio should be considered when prescribing loaded CMJ as training exercises in terms of changed training stimuli or interpreting performance parameters of CMJ with different load conditions.

KEYWORDS: vertical jumps, joint kinetics, barbell load

INTRODUCTION: Countermovement jumps (CMJ) with and without additional loads (up to 80%-100% of body mass) are frequently used in strength training and performance testing. High mechanical power is crucial for athletic performance (Sleivert & Taingahue, 2004). Therefore, loaded vertical jumps are commonly prescribed to increase mechanical power of the lower limbs (Ullrich, Pelzer, & Pfeiffer, 2018). Applying additional loads of 20-30% of body mass are usually recommended to develop explosive strength (Vaverka et al., 2013).
Force and power variables are commonly measured using CMJs to assess athletes' jump height and performance level (Sheppard et al., 2008; Wisløff, Castagna, Helgerud, Jones, & Hoff, 2004). McErlain-Naylor, King, and Pain (2014) found that joint kinetics, especially knee and ankle peak joint power, determine CMJ performance without additional load.
Lower limb power output depends on a complex combination of joint contributions (Fukashiro & Komi, 1987), and CMJ height is likely dependent on athletes' ability to maximally exploit the countermovement phase (unloading + braking phase) (Barker, Harry, & Mercer, 2018). Studies found that a faster unloading phase is associated with an increased storage of elastic strain energy (Barker et al., 2018) and higher CMJ (Harry et al., 2018). Moreover, applying additional loads caused an increased elastic strain energy storage in CMJ (Harry, Barker, & Paquette, 2019) and led to an acute performance increase in subsequently unloaded CMJ (Burkett, Phillips, & Ziuraitis, 2005).
However, the use of additional load during jumping leads to an acute change in total power output by decreasing velocity and increasing force (Samozino, Rejc, Di Prampero, Belli, & Morin, 2012). Additional load increases propulsion phase duration, net impulse, and mean force in the braking and propulsion phase of the jump (Mundy, Smith, Lauder, & Lake, 2017; Vaverka et al., 2013). Joint kinetics such as peak joint power and joint work are affected by additional load as well (Fain, Seymore, Lobb, & Brown, 2021; Fessl, Harbour, Kröll, & Schwameder, 2022). Specifically, during CMJ with increasing additional load, lower limb joint work increases and hip and knee peak joint power decreases (Fessl et al., 2022). Previous studies have evaluated either the total jump or only the propulsion phase of the jump. Hence, it remains unclear if heavy additional load leads to changes in the joint work *ratio* between the braking and propulsion CMJ phases. Therefore, the aim of this study was to investigate the effects of additional load and CMJ joint work and the joint work ratio between the braking and propulsion jump phase.

METHODS: Thirteen male sport students (age: 25.2 ± 3.9 years; body mass: 74.9 ± 6.0 kg; body height: 1.80 ± 0.10 m) volunteered to participate in this study. All participants were physically active and had a strength training background of minimum 3 years (≥ 2h/week). Prior

to the CMJ test session (minimum 48h), participants were familiarized with the specific loaded CMJs. The test session started with a standardized warm up followed by the CMJs with five different load conditions in ascending order: +0%, +20%, +40%, +60%, and +80% of body mass. Participants performed four jumps per load condition, had a break of 1-2 minutes between jumps, and a break of 4 minutes between load conditions. CMJs were performed on two adjacent force plates (1000 Hz; AMTI, Advanced Mechanical, Technology Inc., MSA-6 MiniAmp, Watertown, MA, USA). Simultaneously, body kinematics were recorded using a 12-camera infrared motion capture system (200 Hz; Qualisys AB, Göteborg, Sweden) and a full body marker set (Cleveland Clinical Marker Set). Jump height was calculated by integrating the vertical ground reaction force (GRF) (Kibele, 1998). The start of the CMJ was set when GRF fell below 20 N of the total system load. Braking and propulsion phases were defined according to McMahon, Suchomel, Lake, and Comfort (2018). The braking phase started when GRF crossed body weight line after unweighing and ended when the center of mass reached the lowest position, followed by the propulsion phase which ended at take-off. Net forces and net moments of the hip, knee, and ankle joint were calculated by using an inverse dynamics approach (V3D; C-Motion, Rockville, MD, USA). Net joint power was obtained by multiplying the joint moments with the respective angular velocity. Total joint work was derived by integrating the absolute values of joint power over time (Fain et al., 2021). Joint work ratio between the braking and propulsion phase was expressed as the percentage of the propulsion phase relative to the total work performed in both phases.

All data are presented as group means and standard deviations. A two-way ANOVA with repeated measures was used to identify the main effect of load and CMJ phase on lower limb joint work and a one-way ANOVA with repeated measures was performed to evaluate the main effects of load on joint work ratio using IBM SPSS Statistics (version 26.0; SPSS Inc., Chicago, IL, USA). In case of a significant main effect (only one-way ANOVA, joint work ratio), post hoc analyses (LSD) were conducted for each load condition. Partial eta squared (η^2) effect sizes were calculated and level of significance was set to $\alpha = 0.05$.

RESULTS: Group mean and standard deviation of total joint work of the braking and propulsion CMJ phase at the five different load conditions are presented in Table 1. Total joint work was significantly affected by the additional load (ankle: $p < .001$, $\eta^2 = .818$; knee: $p < .001$, $\eta^2 = .598$; hip: $p < .001$, $\eta^2 = .733$) and CMJ phase (ankle: $p < .001$, $\eta^2 = .982$; knee: $p < .001$, $\eta^2 = .932$; hip: $p < .001$, $\eta^2 = .975$). Significant interaction effects of load and CMJ phase were found for the ankle ($p < .001$, $\eta^2 = .823$) and the knee joint ($p < .001$, $\eta^2 = .465$).

Table 1: Joint Work of the braking and propulsion CMJ phase at 5 different load conditions (Mean ± SD)

		0%	20%	40%	60%	80%
Ankle [J·kg⁻¹]	Brak.	0.07±0.04	0.07±0.03	0.07±0.03	0.09±0.04	0.10±0.05
	Prop.	1.01±0.15	1.13±0.15	1.21±0.18	1.30±0.19	1.44±0.17
Knee [J·kg⁻¹]	Brak.	0.56±0.15	0.72±0.19	0.84±0.20	0.95±0.26	1.07±0.30
	Prop.	1.62±0.32	1.71±0.38	1.80±0.39	1.88±0.49	1.89±0.49
Hip [J·kg⁻¹]	Brak.	0.48±0.12	0.52±0.08	0.63±0.09	0.77±0.16	0.86±0.15
	Prop.	1.44±0.29	1.51±0.21	1.71±0.23	1.84±0.37	1.90±0.27

Brak. = braking CMJ phase; Prop. = propulsion CMJ phase

In Figure 1a-c joint work ratio between the braking and propulsion CMJ phase at five different load conditions are presented. A significant main effect of load on joint work ratio was found for the knee ($p < .001$; $\eta^2 = .865$) and hip ($p < .001$; $\eta^2 = .561$) joint. The ratio of knee and hip joint work in the propulsion phase decreased with increasing load relative to the total joint work produced in both phases. Pairwise comparison (horizontal bars in Figure 1b,c) revealed significant differences for each pair in the knee joint ($p \leq .006$) and for each pair in the hip joint ($p \leq .029$) except for the pairs 0:20, 20:40, and 60:80.
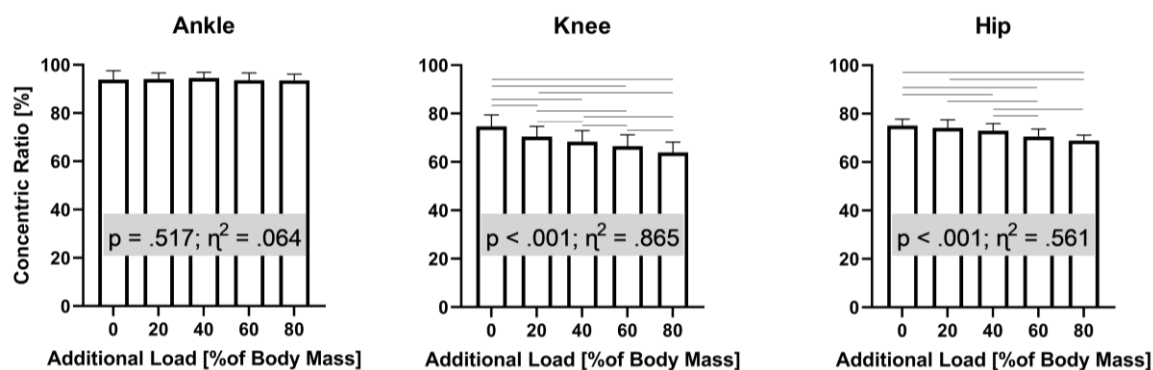
Figure 1a-c: Joint work ratio between the braking and propulsion CMJ phase. p = significance level of the main effect; η^2 = effect size; Horizontal line above the bars indicate significant differences between pairs.

DISCUSSION: The purpose of this study was to investigate the effect of additional load on CMJ joint work and the joint work ratio between the braking and propulsion jump phase. Total joint work of both CMJ phases increased in the ankle, knee, and hip joint as additional load increased. These findings are in line with previous studies (Fain et al., 2021; Feeney, Stanhope, Kaminski, Machi, & Jaric, 2016; Harry et al., 2019) although different forms (weighted vest vs. barbell) and magnitudes (light vs. heavy) of additional load were used.

Propulsion joint work ratio remained stable in the ankle joint and decreased significantly in the knee and hip joint as additional load increased. Moreover, the proportion of joint work during the braking phase increased in the knee and hip joint with increasing additional load. To the best of our knowledge this finding has not yet been reported in the literature; it is unclear the exact origins of these differences, but this topic is outside the scope of this paper. It is known that braking phase characteristics influence CMJ performance (Barker et al., 2018). Hence, these novel findings, not only regarding total joint work increases, but also the increasing braking contributions at the hip and knee, provide useful information for training practice. Braking performance may be improved by applying additional loads in CMJ training. A literature review on accentuated braking loading, defined as higher braking loading compared to the subsequent propulsion loading, reported evidence which indicate substantial long-term effects on muscular performance (Wagle et al., 2017). While the additional load is equal in both phases in loaded CMJ, the effect could be similar. Indeed, it was found that vertical jump training with additional loads maximised CMJ height maximal voluntary contraction of the leg extensor (Ullrich et al., 2018), which could be due to the high braking loading. The importance of high braking muscular performance should not only be considered as a key performance indicator; braking muscle actions are essential in sports which involve energy absorption (e.g. alpine skiing) (Vogt & Hoppeler, 2014) and specific landing tasks (ski jumping, track and field, etc.). Consequently, lower limb braking muscle performance is an important factor for injury prevention especially regarding frontal plane leg stability.

Our findings on altered joint work ratios are particularly relevant when assessing athletes' performance level using loaded CMJ. Since additional load affects body kinematics (Holder, et al, under review) and increases propulsion phase duration as well as mean force in both CMJ phases (Mundy et al., 2017), the parameters of CMJ with different loads should not interpreted equally. All these effects should be considered when applying (heavy) additional loads as they could change training stimuli especially in the braking CMJ phase. More research is needed to fully understand the underlying mechanisms of these joint work differences, particularly the influence of post-activation potentiation, lower limb flexibility, relative lean mass and center of mass shifts.

CONCLUSION: Applying additional load in CMJ leads to an increase of total joint work in the ankle, knee and hip joint, as well as to alteration of the joint work ratio between the braking and propulsion CMJ. These findings suggest that loaded CMJ may be effective for training braking utilization and subsequent athletic performance. Nonetheless, these changes in joint kinetics and body kinematics caused by the additional load should be considered when

prescribing loaded CMJ as training exercise in terms of changed training stimuli or interpreting performance parameters of CMJ with different load conditions.

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