Neuromuscular Impairments in Countermovement Jump Performance Following Heat and Exercise Stress Exposure

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Introduction

The countermovement jump (CMJ) is widely used to assess lower-limb power, neuromuscular (NM) fatigue, and training adaptations in sport and tactical athletes. Both populations frequently operate under high-stress conditions that challenge NM function and recovery. While acute physiological fatigue is reported to impair CMJ performance, the effects of prolonged, multi-phase stress exposure—such as heat and endurance exercise—on CMJ phase-specific mechanics remain unclear.

Purpose

To examine the effects of a 2-phase heat and exercise stress (HES) protocol on CMJ performance

Methods

Fourteen participants (age: 32.1±12.6yrs; 9 Male, 5 Female) completed the procedures. To induce fatigue, participants underwent a 2-phase HES protocol, beginning with 1hr of passive heat exposure in an environmentally controlled room set at 27°C, followed by 90min of stationary cycling under the same thermal conditions. During the HES participants were not allowed to drink water or eat. Following the immediate post-HES exposure testing participants were provided 500mL water and allowed to passively recover for 45min. At each time point (pre-HES, post-HES, and 45min recovery), participants performed 2 CMJ on force plates (30s of rest between jumps). A repeated-measures ANOVA examined CMJ metric changes, with generalized eta squared (η^2G) effect sizes used to assess magnitude of differences. Bonferroni paired t-tests were conducted for post-hoc pairwise comparisons when significant main effects were observed. To further analyze CMJ performance, Principal Component Analysis (PCA) was used to reduce dimensionality, and the transformed data trained a Random Forest (RF) model to predict Pre-HES Post-HES, and Recovery states. Feature importance analysis identified the top 5 principal components (PCs), and the highest-contributing CMJ variables were extracted to determine metrics differentiating fatigue states.

Results

- Following the HES protocol, CMJ performance exhibited significant decrements (Table 1), with jump height ($p=0.005$, $\eta^2G=0.191$) and peak power ($p=0.003$, $\eta^2G=0.072$), decreasing from pre-HES to post-HES and remaining suppressed during recovery.
- During the CMJ eccentric (ECC) phase, deceleration rate of force development (RFD) significantly ($p=0.001$, $\eta^2G=0.224$) declined post-HES, while ECC peak force was reduced ($p=0.023$, $\eta^2G=0.054$). ECC duration was ($p=0.036$, $\eta^2G=0.067$) longer in the recovery phase compared to pre-HES.
- For the concentric (CON) phase, both CON impulse and mean power decreased post-HES ($p<0.001$, $\eta^2G=0.064$-0.097), with impairments persisting into recovery.
- In the landing phase, peak landing force was lower post-fatigue ($p=0.041$, $\eta^2G=0.080$), while force asymmetry decreased ($p=0.023$, $\eta^2G=0.151$).
- The RF model successfully classified HES and recovery states (100% accuracy). PC1, which captured peak power, takeoff velocity, and jump height, was the most important predictor of HES state. PC3 and PC2 (ECC metrics), primarily associated with deceleration RFD and ECC peak force, also played a significant role in classification.

Conclusion

The findings indicate substantial neuromuscular impairments in CMJ performance post-HES, particularly in force-generating capacities during the ECC and CON phases, with persistent reductions in some measures despite a recovery period. Attempts to replicate the findings in larger samples and after exposure to varying types of fatigue and exercise stress are advised for future research.

Practical Applications

The PCA+RF approach may aid in fatigue classification, offering potential applications in sport and tactical athlete populations for workload management and injury prevention strategies.

Main Findings

1. CMJ performance declines significantly after heat and exercise stress and remains impaired even after 45 minutes of recovery.
2. Neuromuscular fatigue is most evident in the eccentric and concentric phases, with reduced RFD, impulse, and power output.
3. Machine learning combined with PCA accurately classified fatigue states, demonstrating the potential of dimensionality reduction and CMJ metrics for monitoring neuromuscular recovery.

Procedures

Pre-Stress CMJ → 1. Passive Heat (60 minutes) → 2. Active Heat (90 minutes) → Post-Stress CMJ → 3. Recovery (45 minutes) → Recovery CMJ

Analysis

CMJ performance and phase specific metrics extracted → Significance testing for changes in metrics → PCA for feature reduction and exploring underlying patterns → Random Forest of PCA data to classify stress states

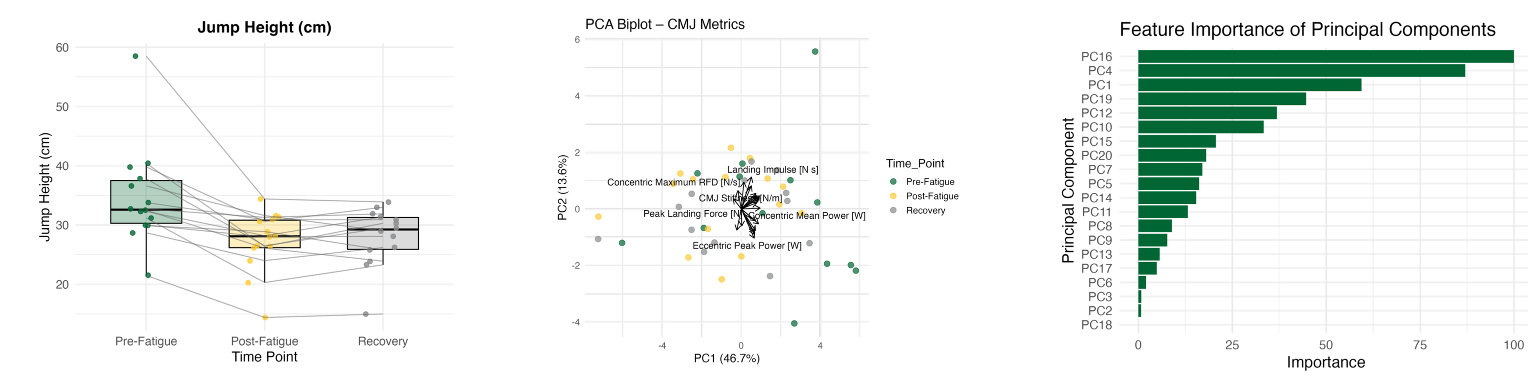
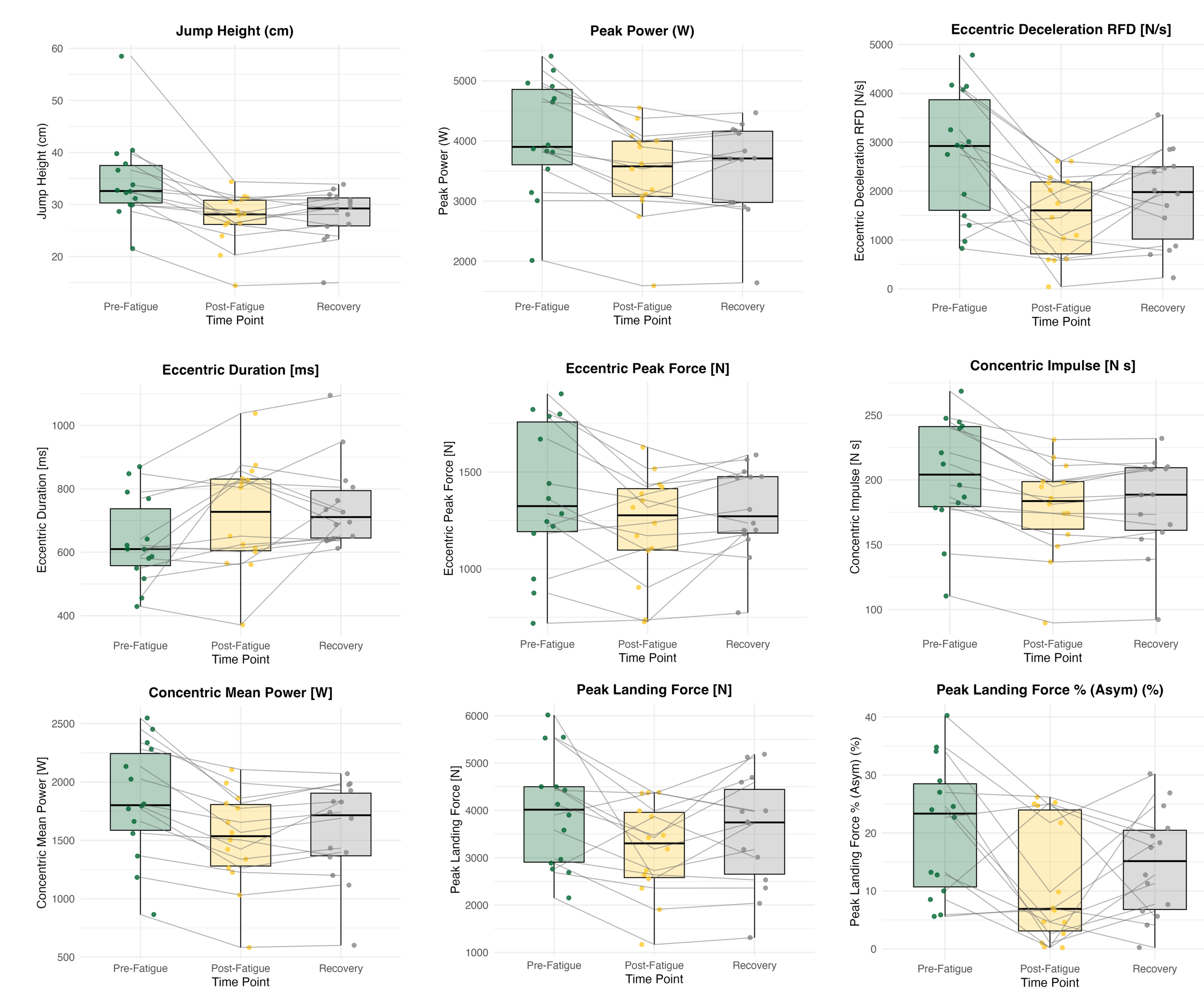


Table 1: Countermovement jump performance metrics across time points

Metric	Pre-Stress	Post-Stress	Recovery	p-value	η²G	Post-hoc comparison
Jump Height (cm)	34.7 (9.3)	27.9 (5.4)	27.9 (5.3)	**0.005**	0.191	Pre > Post; Pre > Rec
Peak Power (W)	4033. 4 (1017.8)	3539.9 (819.4)	3516.5 (840.8)	**0.003**	0.072	Pre > Post; Pre > Rec
CMJ Stiffness (N/M)	4834.6 (1154.8)	4800 (1363.1)	4591.7 (1114.8)	0.687	0.008	
Eccentric Phase						
Braking Impulse (Ns)	49.2 (26.0)	41.4 (19.1)	49.1 (23.6)	0.124	0.027	
Deceleration RFD (N/s)	2832.3 (1287.6)	1528.2 (949.9)	1835.1 (986.4)	**0.001**	0.224	Pre > Post
Duration (ms)	638.8 (126.5)	703.3 (187.6)	731.4 (134.2)	**0.036**	0.067	Rec > Pre
Peak Force (N)	1394.9 (384.4)	1216.2 (313.5)	1304.1 (243.0)	**0.023**	0.054	Pre > Post
Peak Power (W)	1009 (619)	836.5 (331.9)	1005.9 (466.0)	0.093	0.057	
Concentric Phase						
Impulse (Ns)	203.7 (47.7)	180.2 (40.3)	181.8 (40.9)	**<0.001**	0.064	Pre > Post; Pre > Rec
Maximum RFD (N/s)	5342.3 (1545.6)	5708.3 (2144.2)	5380.5 (1717.7)	0.364	0.022	
Duration (ms)	353.5 (86.3)	356.7 (63.3)	352.6 (68.1)	0.899	<0.001	
Peak Force (N)	1748.2 (313.4)	1698.7 (307.6)	1702.1 (326.4)	0.151	0.006	
Mean Power (W)	1842.6 (472.1)	1533.8 (427.9)	1566.5 (427.6)	**<0.001**	0.097	Pre > Post; Pre > Rec
Landing Phase						
Impulse (Ns)	98.4 (38.8)	92.7 (24.0)	97.2 (19.9)	0.745	0.008	
Peak Force (N)	3931.6 (1204.9)	3145 (1064.)	3440.8 (1192.5)	**0.041**	0.080	
Peak Power (W)	4033.4 (1017.8)	3539.9 (819.4)	3516.5 (840.8)	0.072	0.084	
Impulse Asym (%)	14.1 (9.8)	15.4 (13.1)	15.4 (12.3)	0.959	0.003	
Peak Force Asym (%)	23.1 (11.3)	13.4 (11.0)	14.9 (9.1)	**0.023**	0.151	

Note: Values are mean (standard deviation). Generalized eta squared (η²G) effect sizes reported to assess the magnitude of differences. Effect sizes were interpreted using the following thresholds: small (η²G > 0.01), medium (η²G > 0.06), and large (η²G ≥ 0.14). Abbreviations: Asym, asymmetry; Rec, recovery.

CMJ Metrics with Significant Changes



PCA and Random Forest Modeling