

## Acute neuromuscular responses in young trail runners: Immediate, post-, and delayed effects on squat and countermovement jump performance

LUIS FERMIN SANCHEZ-GARCIA<sup>1</sup>, NURIA MOLINA-GARCIA<sup>2</sup>, JOSE M. JIMENEZ-OLMEDO<sup>3</sup>,  
<sup>1,2,3</sup>Department of General Didactic and Specific Didactic, University of Alicante, Alicante, SPAIN

Published online: February 28, 2026

Accepted for publication: February 15, 2026

DOI:10.7752/jpes.2026.02027

### Abstract

This study investigated the acute neuromuscular responses to a competitive mountain trail race in young elite and well-trained runners by analyzing changes in squat jump (SJ), countermovement jump (CMJ), and the derived elastic component (CMJ–SJ). Thirty-six participants (29 men, 7 women;  $18.3 \pm 1.2$  years), competed in a 14.20 km trail running race with a positive elevation gain of 420 m. Each participant performed two SJ and two CMJ trials at three points: before the race (PRE), immediately after finishing (POST), and approximately 5-7 min post-race (POST5). The best attempt of each test was recorded using a Chronojump Bosco System® platform. Data satisfied normality assumptions and were analyzed using a two-way repeated-measures ANOVA (time  $\times$  sex). Significant main effects of time were observed for both SJ ( $F(1.33, 45.34) = 17.75, p < .001, \eta_p^2 = .34$ ) and CMJ ( $F(1.16, 39.54) = 23.71, p < .001, \eta_p^2 = .41$ ). Post hoc analyses revealed a potentiation effect immediately after the race (PRE < POST,  $p < .001$ ) followed by a significant decrease after 5-7 minutes (POST > POST5,  $p < .01$ ), with values falling below baseline (PRE > POST5,  $p < .05$ ). No significant changes were detected in the elastic component ( $p = .60$ ), suggesting that the stretch–shortening efficiency remained stable. These findings indicate that short-duration trail running elicits a transient enhancement of lower-limb power likely associated with post-activation potentiation, followed by neuromuscular fatigue. Monitoring jump performance may therefore provide a sensitive tool for tracking acute load and recovery in young endurance athletes.

**Keywords:** Muscle fatigue, post-activation potentiation, mountain running, youth endurance athletes, Bosco test.

### Introduction

Optimizing athletic success in high-level endurance running requires increasing technical and scientific sophistication, making precise monitoring and adjustment of the training load essential for performance maximization. In this context, strength and power are recognized as critical components describing an individual's capacity for physical exertion (Kyne & Cronin, 2025). In endurance sports, maximal force capacity and muscle endurance are highly correlated with running ability, (Lemire et al., 2021). Furthermore, having a strong muscular foundation is vital for runners to repeatedly absorb the high ground reaction forces generated, particularly at higher speeds or when carrying a load (Cáceres-Diego et al., 2025). Indeed, maximal lower limb strength and leg musculotendinous stiffness emerge as significant predictors of performance, especially during downhill running (Lemire et al., 2021).

However, despite the well-established role of strength and stiffness in endurance performance, the neuromuscular responses of young trail runners remain largely unexplored. Young athletes differ from adults in terms of physiological maturity, training adaptation, and recovery capacity, which may influence how their neuromuscular system responds to high-intensity or prolonged trail running efforts.

To assess the neuromuscular impact of athletic demands, the **countermovement jump (CMJ)** and the **squat jump (SJ)** are widely employed. These tests are recognized as practical and valid methods to indirectly evaluate the function of the Stretch-Shortening Cycle (SSC) and the capacity for rapid force production. The SJ is defined by initiating the jump after holding a squat position for 3–4 seconds, which dissipates stored elastic energy. Consequently, the SJ serves as a baseline measure of an athlete's ability to produce concentric force, reflecting primarily the muscle's Contractile Component (CC). Conversely, the CMJ incorporates a preparatory countermovement that precedes the concentric phase, leveraging the SSC phenomenon to augment force, velocity, and power output (Kyne & Cronin, 2025). The CMJ provides valuable insight into the utilization of the eccentric phase (Van Hooren & Zolotarjova, 2017) and is often utilized as a model to study naturally occurring neuromuscular fatigue (Nicol et al., 2006 in Rousanoglou et al., 2016). Recent reviews, however, have questioned the reliability of CMJ jump height alone as a fatigue marker in endurance athletes, as post-activation potentiation (PAP) may transiently mask fatigue-related decrements (García-Pinillos et al., 2021; Miras Moreno, 2020). Therefore, incorporating both CMJ and SJ may provide a more complete understanding of concentric and eccentric force production during and after endurance events.

As Rousanoglou et al. (2016) indicated, *Prolonged exercise significantly impairs strength and power*. High-intensity, long-duration running induces functional alterations and reduces the capacity for maximal force generation. Ultra-endurance events lead to structural muscle damage and a substantial impairment in maximal force production capacity. For instance, maximal isometric knee extension force has been reported to decrease by 24% following a 30 km race and by 30% after a 65 km ultra-marathon, (Easthope et al., 2010). In mountain *trail running*, the resulting fatigue is frequently specific to **eccentric muscle work**, a key determinant of downhill performance. This specificity is often reflected in a pattern of post-race reductions in vertical jump mechanics, where impairments in the eccentric phase typically precede those in the concentric phase (Rousanoglou et al., 2016).

Similar findings have been reported in ultra-endurance events, where significant post-race decreases in CMJ and SJ performance were observed along with biochemical markers of muscle damage, indicating neuromuscular fatigue particularly in the lower limbs (Millet et al., 2011). However, the magnitude of these alterations depends strongly on race distance, elevation profile, and athlete experience. Research into post-exercise fatigue measured via CMJ reveals varied outcomes across sports modalities:

- **Long-Distance Running:** Significant decreases in jump height (JH) have been widely reported following marathons (~13% reduction in Nicol et al., (1991) or ~22% in Del Coso et al., (2013). Maximal voluntary contraction (MVC) torque can decrease by 32–40% after a 55 km trail race (Easthope et al., 2010).
- **Mountain Half-Marathon:** One study showed that JH did not decrease significantly immediately after a mountain half-marathon (-4.1%) due to possible **post-activation potentiation (PAP)**, but the reduction became significant five minutes later (-7.9%) (Rousanoglou et al., 2016b).
- **Sprinting:** In elite sprinters, the magnitude of CMJ height loss correlates strongly and inversely with acute metabolic fatigue markers, showing high correlations with blood lactate ( $R^2=0.96$ ) and blood ammonia ( $R^2=0.95$ ) (Jimenez-Reyes et al., (2016) in Miras Moreno, (2020)). Moreover, greater sprint distance leads to greater CMJ losses (3.1% loss for 40m rising to 8.3% loss for 80m sprints).
- **Military/Loaded Running:** In young marines, a 5 km loaded time trial induced an initial potentiation (increase) in lower-body power (VJ CMJ) immediately post-test, attributed to heightened psychophysiological activation. However, these values subsequently declined significantly below baseline levels 24 and 48 hours later (Cáceres-Diego et al., 2025).

Recent evidence also supports that traditional CMJ height may not fully reflect neuromuscular fatigue in trail running. In elite mountain runners competing at the 2023 Trail Running World Championship, Jaén-Carrillo et al. (2025) observed no significant post-race reduction in CMJ height or peak power, although the Reactive Strength Index (RSI) decreased significantly, indicating that jump height alone may underestimate acute fatigue when potentiation mechanisms are active.

While considerable research exists focusing on adult endurance runners (average age of participants often around 41.3 years in Rousanoglou et al. (2016), or master athletes around 45.9 years in Easthope et al.(2010) or elite populations, there is a distinct lack of studies analyzing acute alterations in strength and power, measured by CMJ and SJ, in young mountain runners immediately following a trail running event. Understanding these responses in youth athletes could provide valuable insights into fatigue management, recovery strategies, and the validity of CMJ and SJ as field tools for neuromuscular monitoring in this developing population.- Therefore, the primary objective of the present study is to analyze the acute changes in lower-limb strength and power, quantified through countermovement jump(CMJ) and squat jump(SJ) performance, in young mountain runners immediately pre- and post-competition in a trail running race.

## Material & methods

### Participants

A total of 36 young Spanish trail runners aged between 15 and 20 years (29 male age  $18.38 \pm 1.15$ , height  $170.41 \pm 5.48$  cm, weight  $59.83 \pm 10.16$  kg; 7 female age  $18.18 \pm 1.21$ , height  $163.14 \pm 3.72$  cm, weight  $54.00 \pm 4.76$  kg), all belonging to a mountain running technification program and some of them elite trail runners in their categories, took part in the present study.

All subjects signed a written informed consent before participation, including written parental consent for trail runners aged <18 years old. The study protocol was conducted according to the guidelines of the Declaration of Helsinki and was approved by the Ethics Committee of the University of Alicante. All procedures were carried out in compliance with institutional guidelines and national regulations. Prior to participation, all individuals provided written informed consent. Additional written consent was obtained for the publication of any potentially identifiable information or images contained within this article

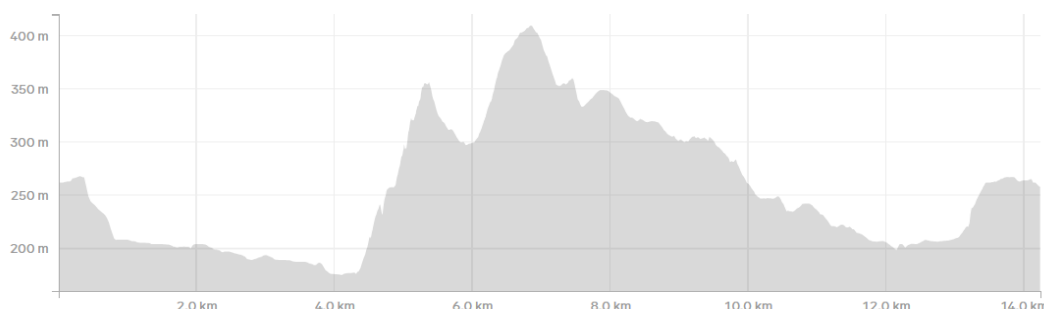
### Procedure

All participants were previously informed and trained in the execution of both jump tests during prior training sessions in order to ensure proper technical performance.

On the day of testing, three data collection points were established:

1. **PRE:** Approximately one hour before the start of the race, athletes gathered for the pre-test. Each participant performed one familiarization jump to confirm correct execution, followed by two squat jumps (SJ) and two countermovement jumps (CMJ). The best result of each type of jump was recorded for analysis. To optimize data collection, all participants first performed the SJ trials and subsequently the CMJ trials. Individual data collection sheets had been prepared in advance during the previous training camp.
2. **Race:** The participants in the study completed a 14.20 km trail running race with a positive elevation gain of 420+ m, the course profile of which is shown in Figure 1
3. **POST:** Immediately after finishing the race (between the first and second minute after crossing the finish line), athletes performed the following jump protocol: one SJ, 20 seconds of rest, another SJ, one minute of rest, one CMJ, 20 seconds of rest, and a final CMJ.
4. **POST 5:** After a rest period of approximately 5 to 7 minutes, the same jump protocol described in the POST test was repeated.

**Figure 1.**  
*Trail running race profile*



Data concerning these jumps were measured with jumping platform (Chronojump, Bosco Systems®, Barcelona, Spain), validated in (Pueo et al., 2020).

#### *Statistical Analysis*

Statistical analysis was performed using the Statistical Package for Social Sciences (SPSS V27.0 for Windows, IBM Corp., Armonk, NY, USA). Descriptive analysis was used to obtain the frequencies and percentages of all the variables. A mixed two-way repeated-measures ANOVA was conducted to examine the effects of time (PRE, POST, POST 5) and sex (male, female) on jump performance variables (SJ, CMJ, and elastic component). The assumption of normality was verified using the Shapiro–Wilk test, and sphericity was assessed with Mauchly’s test. When the sphericity assumption was violated, the Greenhouse–Geisser correction was applied. Post hoc pairwise comparisons with Bonferroni adjustments were performed to identify differences between time points. (Cohen, 2013). The statistical significance was set at  $p < 0.05$ .

#### **Results**

A preliminary analysis of the jumps performed before the race shows that men achieved an average of  $27.48 \text{ cm} \pm 5.85$  in SJ and  $29.83 \text{ cm} \pm 5.86$  in CMJ, while women reached an average of  $21.79 \text{ cm} \pm 3.20$  in SJ and  $23.61 \text{ cm} \pm 3.21$  in CMJ. From these values, the mean elastic component (CMJ – SJ) can be calculated for both men ( $2.34 \text{ cm} \pm 3.55$ ) and women ( $1.86 \text{ cm} \pm 2.77$ ) (Table 1). We can also see in this table the averages in SJ, CMJ and elastic component after the race and post 5 minutes in all cases men values are higher than women values.

**Table 1** *Descriptive statistics for jump performance across time and sex (mean  $\pm$  SD, cm)*

| Variable          | Time   | Men (n = 29)     | Women (n = 7)    | Total (N = 36)   |
|-------------------|--------|------------------|------------------|------------------|
| SJ                | PRE    | $27.48 \pm 5.85$ | $21.79 \pm 3.20$ | $26.38 \pm 5.86$ |
|                   | POST   | $30.15 \pm 4.99$ | $22.69 \pm 2.93$ | $28.70 \pm 5.51$ |
|                   | POST 5 | $25.27 \pm 5.23$ | $20.06 \pm 2.95$ | $24.25 \pm 5.27$ |
| CMJ               | PRE    | $29.83 \pm 5.86$ | $23.61 \pm 3.21$ | $28.62 \pm 5.95$ |
|                   | POST   | $32.24 \pm 5.86$ | $23.71 \pm 3.29$ | $30.58 \pm 6.41$ |
|                   | POST 5 | $27.86 \pm 5.60$ | $21.39 \pm 3.44$ | $26.60 \pm 5.82$ |
| Elastic component | PRE    | $2.34 \pm 3.55$  | $1.83 \pm 2.77$  | $2.24 \pm 3.38$  |
|                   | POST   | $2.09 \pm 4.06$  | $1.02 \pm 3.39$  | $1.88 \pm 3.91$  |
|                   | POST 5 | $2.59 \pm 2.95$  | $1.33 \pm 1.88$  | $2.35 \pm 2.80$  |

*Note.* SJ = squat jump; CMJ = countermovement jump; POST 5 corresponds to approximately 5–7 minutes after the race.

The assumption of normality was tested using Shapiro–Wilk test for all dependent variables (SJ, CMJ, and Elastic Component) across the three measurement points (PRE, POST, and POST5) and by sex. All distributions met the normality assumption ( $p > .05$ ), except for the elastic component PRE in men ( $p = .028$ ), which showed a minor deviation from normality. Since T test and ANOVA procedures are considered robust against slight departures from normality, particularly with balanced group sizes and continuous data, subsequent analyses were conducted using **parametric tests**

A T test comparing by sex (Table 2) revealed that male participants achieved significantly higher scores than female participants in both the squat jump (SJ) and the countermovement jump (CMJ) across all three assessment time points ( $p < 0.05$ ). However, this trend was not observed for the "elastic component" variable—calculated as the difference between CMJ and SJ performance (CMJ–SJ)—which yielded comparable values for both men and women. These findings indicate that the relative height gains provided by the stretch-shortening cycle during a CMJ compared to an SJ are proportional regardless of sex.

**Table 2** *T test results comparing by sex for the different jumps and moments*

| JUMP                | t     | gl     | Sig. (p)        | media difference | Standard error difference |
|---------------------|-------|--------|-----------------|------------------|---------------------------|
| SJ PRE              | 2.471 | 34     | <b>.019</b>     | 5.696            | 2.305                     |
| CMJ PRE             | 2.688 | 34     | <b>.011</b>     | 6.211            | 2.310                     |
| Elastic Comp.PRE    | 0.416 | 11,308 | .685            | .516             | 1.238                     |
| SJ POST             | 3.777 | 34     | <b>&lt;.001</b> | 7.460            | 1.975                     |
| CMJ POST            | 3.690 | 34     | <b>&lt;.001</b> | 8.534            | 2.313                     |
| Elastic Comp.POST   | .646  | 34     | .522            | 1.074            | 1.661                     |
| SJ POST 5           | 2.521 | 34     | <b>.017</b>     | 5.207            | 2.066                     |
| CMJ POST 5          | 2.908 | 34     | <b>.006</b>     | 6.466            | 2.224                     |
| Elastic Comp.POST 5 | 1.072 | 34     | .291            | 1.259            | 1.175                     |

*Note.* SJ = Squat Jump; CMJ = Countermovement Jump; POST 5=5-7 min after the race.  $p < .05$  indicates significative differences.

Pairwise comparisons (Table 3) revealed a significant improvement in both SJ and CMJ immediately after the mountain race (PRE–POST,  $p < .001$ ), followed by a marked decline ten minutes later (POST–POST 5,  $p < .01$ ). Performance values at POST5 dropped below baseline for both jump types (PRE–POST 5,  $p < .05$ ), indicating transient fatigue after the initial potentiation. In contrast, the elastic component (CMJ – SJ) showed no significant changes across any interval ( $p > .60$ ), suggesting that alterations in jump height were primarily driven by overall neuromuscular output rather than modifications in stretch-shortening efficiency.

**Table 3** *Pairwise comparisons between time points for jump performance variables*

| Variable      | Contrast      | Mean Difference (ΔM) | Sig. (p) | Cohen's d / r (effect size)  | Interpretation                                      |
|---------------|---------------|----------------------|----------|------------------------------|-----------------------------------------------------|
| SJ            | PRE → POST    | +2.32 cm             | < .001   | $d = 0.63$ (moderate)        | Significant increase → post-activation potentiation |
|               | PRE → POST 5  | –2.12 cm             | .013     | $d = 0.55$ (moderate)        | Significant decrease → post-exercise fatigue        |
|               | POST → POST 5 | –4.44 cm             | < .001   | $d = 0.78$ (large)           | Significant loss from immediate to delayed test     |
| CMJ           | PRE → POST    | +1.96 cm             | < .001   | $d = 0.67$ (moderate)        | Significant improvement after race                  |
|               | PRE → POST 5  | –2.02 cm             | .021     | $d = 0.58$ (moderate)        | Drop below baseline after 5 min recovery            |
|               | POST → POST 5 | –3.98 cm             | .008     | $d = 0.76$ (large)           | Performance decline from POST to POST 5             |
| Elastic comp. | PRE → POST    | –0.36 cm             | .60      | $r \approx .10$ (small)      | No significant change                               |
|               | PRE → POST 5  | +0.11 cm             | .73      | $r \approx .05$ (negligible) | Stable elastic contribution                         |
|               | POST → POST 5 | +0.47 cm             | .67      | $r \approx .06$ (negligible) | No difference                                       |

*Note.* Positive values indicate higher post-test means; negative values indicate decreases relative to the earlier condition. SJ = Squat Jump; CMJ = Countermovement Jump; POST5 ≈ 5-7 min after race. Effect sizes are approximated from partial  $\eta^2$  or t-based contrasts; thresholds: small=.20, moderate=.50, large=.75 (Cohen, 1988).

A series of mixed repeated-measures ANOVAs were conducted to evaluate the effects of time (PRE, POST, POST5) and sex (men, women) on squat jump (SJ), countermovement jump (CMJ), and the derived

elastic component (CMJ – SJ). Both SJ and CMJ increased immediately after the mountain race (POST) — likely due to post-activation potentiation.

At POST5, both measures decreased below baseline, reflecting fatigue accumulation. The elastic component (difference CMJ – SJ) remained unchanged, implying that changes in jump height were mainly due to overall neuromuscular performance rather than stretch–shortening efficiency.

Sex differences: men displayed consistently higher jump values, but their temporal response (pattern of change) was similar to women's.

**Table 4** Repeated-measures ANOVA results for jump performance variables

| Variable          | Effect            | df          | F     | p      | Partial $\eta^2$ | Correction         |
|-------------------|-------------------|-------------|-------|--------|------------------|--------------------|
| SJ                | Time              | 1.33, 45.34 | 17.75 | < .001 | .34              | Greenhouse–Geisser |
|                   | Time $\times$ Sex | 1.33, 45.34 | 1.76  | .19    | .05              | Greenhouse–Geisser |
|                   | Sex (between)     | 1, 34       | 9.46  | .004   | .22              | —                  |
| CMJ               | Time              | 1.16, 39.54 | 23.71 | < .001 | .41              | Greenhouse–Geisser |
|                   | Time $\times$ Sex | 1.16, 39.54 | 3.36  | .068   | .09              | Greenhouse–Geisser |
|                   | Sex (between)     | 1, 34       | 10.23 | .003   | .23              | —                  |
| Elastic component | Time              | 1.34, 45.50 | 0.38  | .60    | .01              | Greenhouse–Geisser |
|                   | Time $\times$ Sex | 1.34, 45.50 | 0.19  | .74    | .01              | Greenhouse–Geisser |
|                   | Sex (between)     | 1, 34       | 0.59  | .45    | .02              | —                  |

*Note.* Mauchly's test of sphericity was violated for all models ( $p < .001$ ); Greenhouse–Geisser corrections were applied. SJ = squat jump; CMJ = countermovement jump.

In order to explain the results of Table 4 it's important to describe the obtained values and its meanings.

#### Squat jump (SJ)

Mauchly's test indicated that the assumption of sphericity was violated ( $W = .50$ ,  $\chi^2(2) = 22.85$ ,  $p < .001$ ); therefore, Greenhouse–Geisser corrections ( $\epsilon = .67$ ) were applied. The analysis revealed a significant main effect of time,  $F(1.33, 45.34) = 17.75$ ,  $p < .001$ ,  $\eta^2_p = .34$ , indicating that SJ height differed across time points.

Post hoc pairwise comparisons showed a significant increase from PRE to POST ( $p < .001$ ) followed by a significant decrease from PRE to POST 5 ( $p = .013$ ). The time  $\times$  sex interaction was not significant ( $p = .19$ ), suggesting similar temporal trends for men and women.

The between-subjects effect of sex was significant,  $F(1, 34) = 9.46$ ,  $p = .004$ ,  $\eta^2_p = .22$ , with men exhibiting higher SJ values than women.

#### Countermovement jump (CMJ)

Mauchly's test also showed a violation of sphericity ( $W = .28$ ,  $\chi^2(2) = 41.97$ ,  $p < .001$ ); Greenhouse–Geisser correction ( $\epsilon = .58$ ) was applied.

A significant main effect of time emerged,  $F(1.16, 39.54) = 23.71$ ,  $p < .001$ ,  $\eta^2_p = .41$ , indicating substantial variations in CMJ performance across testing moments. Pairwise analyses demonstrated a marked increase from PRE to POST ( $p < .001$ ), followed by a significant decline from POST to POST 5 ( $p = .008$ ), with POST 5 values still lower than PRE ( $p = .021$ ). The time  $\times$  sex interaction was not significant after correction ( $p = .068$ ), though a moderate tendency suggested a slightly greater decline in women.

The between-subjects effect of sex was significant,  $F(1, 34) = 10.23$ ,  $p = .003$ ,  $\eta^2_p = .23$ , with men outperforming women at all time points.

#### Elastic Component (CMJ – SJ)

Mauchly's test indicated sphericity violation ( $W = .51$ ,  $\chi^2(2) = 22.52$ ,  $p < .001$ ); Greenhouse–Geisser correction ( $\epsilon = .67$ ) was applied. No significant main effect of time was observed,  $F(1.34, 45.50) = .38$ ,  $p = .60$ ,  $\eta^2_p = .01$ , indicating that the elastic contribution did not change across time points. Neither the time  $\times$  sex interaction ( $p = .74$ ) nor the between-subjects effect of sex ( $p = .45$ ) reached significance. These findings suggest that while absolute jump heights changed over time, the proportion of the elastic component remained stable.

### **Discussion**

The baseline results of the current study (Table 1) show jump heights in males (SJ:  $27.48 \pm 5.85$  cm; CMJ:  $29.83 \pm 5.86$  cm) and females (SJ:  $21.79 \pm 3.20$  cm; CMJ:  $23.61 \pm 3.21$  cm) that closely align with profiles recently described for young developmental trail runners (Sanchez-García et al., 2022). Comparing these data with other disciplines, we observe that these values are considerably lower than those in explosive sports such as volleyball (CMJ > 40 cm) or basketball (Riggs & Sheppard, 2009; Sanchez-García et al., 2022). This disparity is attributed to the specificity of endurance training, which prioritizes type I fibers and running economy over explosive power (García-Pinillos et al., 2021).

Regarding sex differences, males exhibited significantly higher values in SJ and CMJ across all measurement points ( $p < .05$ , Table 2). This dimorphism is a constant in the literature and is explained by biological factors: males possess greater lean muscle mass, lower body fat percentages, and a more efficient

motor unit recruitment capacity (Navalta et al., 2018). However, the **elastic component** variable (CMJ-SJ) showed no significant differences between sexes. This suggests that despite differences in absolute strength, the efficiency of the Stretch-Shortening Cycle (SSC) and the ability to utilize elastic energy stored during the eccentric phase are proportional in both sexes, a finding that reinforces the idea that SSC mechanisms are independent of muscle size in young runners (Van Hooren & Zolotarjova, 2017).

#### Neuromuscular Evolution: Potentiation and Fatigue

The most significant finding of this study is the marked increase in performance immediately after the race (POST) in both SJ and CMJ ( $p < 0.001$ , Table 3). This result contradicts studies on ultra-distance races (108 km), where massive strength losses are reported (Pradas et al., 2021), but aligns with research on shorter or submaximal intensity events. This immediate improvement is attributed to **Post-Activation Performance Enhancement (PAPE)**, a phenomenon where previous muscle contractions (especially the eccentric work from descents) increase the phosphorylation of myosin light chains, facilitating greater explosive force production (García-Pinillos et al., 2021). Similar results of initial potentiation have been documented in young marines after 5 km loaded runs (Cáceres-Diego et al., 2025) and in endurance runners following incremental protocols (Boullosa et al., 2011).

However, this mechanical advantage is short-lived. At 5-7 minutes post-race (POST 5), performance drops significantly below baseline values. This pattern matches exactly with the findings of Rousanoglou et al., (2016) in a mountain half-marathon, where CMJ only decreased by 4.1% at the finish line, but the loss reached 7.9% five minutes later. The explanation lies in the fact that PAPE temporarily masks neuromuscular fatigue; once the psychophysiological activation state and muscle temperature decline, the accumulated fatigue (structural damage to the sarcomere and excitation-contraction coupling failure) manifests fully (Millet et al., 2011; Rousanoglou et al., 2016).

Furthermore, recent evidence from Jaén-Carrillo et al. (2025), suggests that traditional jump height might not fully reflect acute fatigue in elite trail runners even when other metrics, such as the **Reactive Strength Index (RSI)**, show significant decreases. This indicates that athletes may alter their jump strategy—becoming less reactive—to maintain height despite being fatigued. In our study, the Stability of the Elastic Component (CMJ-SJ) across all time points ( $p > 0.60$ ) supports this notion. The lack of change in the elastic contribution implies that fatigue in young runners does not selectively impair the Stretch-Shortening Cycle (SSC) efficiency; rather, it induces a global reduction in neuromuscular output that only becomes visible once PAPE dissipates. This is consistent with Kyne & Cronin (2025), who argue that while CMJ and SJ provide distinct insights into contractile and elastic facets of muscle function, jump height is a limited variable that does not capture underlying movement strategy shifts

#### Conclusions

1. Trail running in young athletes induces an initial state of neuromuscular potentiation that improves vertical jump height immediately after crossing the finish line.
2. There is a critical fatigue window appearing after 5 minutes of rest, where the loss of strength overcomes potentiation mechanisms.
3. There are differences in SJ and CMJ performance due to biological aspects, but there are no differences in elastic efficiency between young males and females, indicating similar neuromuscular maturation in the utilization of the SSC.
4. For coaches, CMJ and SJ are valid tools for monitoring fatigue, but their predictive reliability is strictly dependent on the timing of assessment. Measuring immediately post-race may yield "false positives" of performance due to PAPE.
5. In young trail runners, a five-minutes rest window is necessary to allow potentiation to subside and for true neuromuscular fatigue to manifest as a decline in jump height.
6. The Elastic Component remains stable despite acute exhaustion, indicating that the proportional gains from the SSC are a robust neuromuscular trait rather than a sensitive marker of acute fatigue in this population.
7. Practitioners should supplement jump height with other variables, such as RSI or force-time signatures, to gain a more comprehensive understanding of fatigue and recovery strategies in trail running

#### Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors did not use generative AI or AI-assisted technologies. All the tests, data analyses processes and writing were developed by the authors using the tools described above.

#### Conflicts of interest and funding

- The authors declare no conflicts of interest.
- No external funding was received for the conduct of this study.

#### References

- Boullosa, D. A., Tuimil, J. L., Alegre, L. M., Iglesias, E., & Lusquinos, F. (2011). Concurrent fatigue and potentiation in endurance athletes. *International Journal of Sports Physiology and Performance*, 6(1), 82–93. <https://doi.org/10.1123/IJSP.6.1.82>

- Cáceres-Diego, B., Alcaraz, P. E., & Marín-Pagán, C. (2025). Neuromuscular Responses to 5 K Time Trial Load Carried by Spanish Army Marines. *Sports* 2025, Vol. 13, Page 129, 13(4), 129. <https://doi.org/10.3390/SPORTS13040129>
- Cohen, J. (2013). Statistical Power Analysis for the Behavioral Sciences. *Statistical Power Analysis for the Behavioral Sciences*, 1–567. <https://doi.org/10.4324/9780203771587/STATISTICAL-POWER-ANALYSIS-BEHAVIORAL-SCIENCES-JACOB-COHEN/RIGHTS-AND-PERMISSIONS>
- Del Coso, J., Fernández, D., Abián-Vicen, J., Salinero, J. J., González-Millán, C., Areces, F., Ruiz, D., Gallo, C., Calleja-González, J., & Pérez-González, B. (2013). Running pace decrease during a marathon is positively related to blood markers of muscle damage. *PloS One*, 8(2). <https://doi.org/10.1371/JOURNAL.PONE.0057602>
- Easthope, C. S., Hausswirth, C., Louis, J., Lepers, R., Vercruyssen, F., & Brisswalter, J. (2010). Effects of a trail running competition on muscular performance and efficiency in well-trained young and master athletes. *European Journal of Applied Physiology*, 110(6), 1107–1116. <https://doi.org/10.1007/s00421-010-1597-1>
- García-Pinillos, F., Ramírez-Campillo, R., Boullosa, D., Jiménez-Reyes, P., & Latorre-Román, P. (2021). Vertical Jumping as a Monitoring Tool in Endurance Runners: A Brief Review. *Journal of Human Kinetics*, 80(1), 297. <https://doi.org/10.2478/HUKIN-2021-0101>
- Jaén-Carrillo, D., García-Pinillos, F., Alcaraz, P. E., Marín-Pagán, C., Martínez-Noguera, F. J., & Federolf, P. A. (2025). Jump performance and handgrip strength do not reflect acute fatigue in elite trail runners after the 2023 world trail running championship. *Frontiers in Sports and Active Living*, 7. <https://doi.org/10.3389/FSPOR.2025.1506067>
- Jimenez-Reyes, P., Pareja-Blanco, F., Cuadrado-Peñafiel, V., Morcillo, J. A., Párraga, J. A., & González-Badillo, J. J. (2016). Mechanical, Metabolic and Perceptual Response during Sprint Training. *International Journal of Sports Medicine*, 37(10), 807–812. <https://doi.org/10.1055/S-0042-107251>
- Kyne, H., & Cronin, J. B. (2025). Beyond Jump Height: A Comparison of Concentric Variables in the Squat Jump, countermovement jump and Drop Jump for Athletic Profiling. *Sports* 2025, Vol. 13, Page 379, 13(11), 379. <https://doi.org/10.3390/SPORTS13110379>
- Lemire, M., Hureau, T. J., Favret, F., Geny, B., Kouassi, B. Y. L., Boukhari, M., Lonsdorfer, E., Remetter, R., & Dufour, S. P. (2021). Physiological factors determining downhill vs uphill running endurance performance. *Journal of Science and Medicine in Sport*, 24(1), 85–91. <https://doi.org/10.1016/J.JSAMS.2020.06.004>
- Millet, G. Y., Tomazin, K., Verges, S., Vincent, C., Bonnefoy, R., Boisson, R. C., Gergelé, L., Féasson, L., & Martin, V. (2011). Neuromuscular Consequences of an Extreme Mountain Ultra-Marathon. *PLOS ONE*, 6(2), e17059. <https://doi.org/10.1371/JOURNAL.PONE.0017059>
- Miras Moreno, S. (2020). La altura del salto en contramovimiento como instrumento de control de la fatiga neuromuscular. Revisión sistemática (Counter-movement Jump height as a means to monitor neuromuscular fatigue. Systematic Review). *Retos*, 37, 820–826. <https://doi.org/10.47197/retos.v37i37.73302>
- Nicol, C., Avela, J., & Komi, P. V. (2006). The stretch-shortening cycle : a model to study naturally occurring neuromuscular fatigue. *Sports Medicine (Auckland, N.Z.)*, 36(11), 977–999. <https://doi.org/10.2165/00007256-200636110-00004>
- Nicol, C., Komi, P. V., & Marconnet, P. (1991). Fatigue effects of marathon running on neuromuscular performance. *Scandinavian Journal of Medicine & Science in Sports*, 1(1), 10–17. <https://doi.org/10.1111/J.1600-0838.1991.TB00265.X>
- Pradas, F., Falcón, D., Peñarrubia-Lozano, C., Toro-Román, V., Carrasco, L., & Castellar, C. (2021). Effects of Ultratrail Running on Neuromuscular Function, Muscle Damage and Hydration Status. Differences According to Training Level. *International Journal of Environmental Research and Public Health* 2021, Vol. 18, Page 5119, 18(10), 5119. <https://doi.org/10.3390/IJERPH18105119>
- Pueo, B., Penichet-Tomas, A., & Jimenez-Olmedo, J. M. (2020). Reliability and validity of the Chronojump open-source jump mat system. *Biology of Sport*, 37(3), 255–259. <https://doi.org/10.5114/biolSport.2020.95636>
- Riggs, M. P., & Sheppard, J. M. (2009). The relative importance of strength and power qualities to vertical jump height of elite beach volleyball players during the counter-movement and squat jump. *Journal of Human Sport and Exercise*, 4(3), 221–236. <https://doi.org/10.4100/JHSE.2009.43.04>
- Rousanoglou, E. N., Noutsos, K., Pappas, A., Bogdanis, G., Vagenas, G., Bayios, I. A., & Boudolos, K. D. (2016). Alterations of Vertical Jump Mechanics after a Half-Marathon Mountain Running Race. *Journal of Sports Science & Medicine*, 15(2), 277. <https://pmc.ncbi.nlm.nih.gov/articles/PMC4879441/>
- Sanchez-García, L. F., Pueo, B., Penichet-Tomás, A., & Jiménez-Olmedo, J. M. (2022). Strength profile in young male and female trail runners. *Journal of Physical Education and Sport*, 22(1), 266–272. <https://doi.org/10.7752/JPES.2022.01034>
- Van Hooren, B., & Zolotarjova, J. (2017). The Difference between Countermovement and squat jump Performances: A Review of Underlying Mechanisms with Practical Applications. In *Journal of Strength and Conditioning Research* (Vol. 31, Issue 7). <https://doi.org/10.1519/JSC.0000000000001913>