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Research article

Alterations of Vertical Jump Mechanics after a Half-Marathon Mountain Running Race

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Abstract
The fatiguing effect of long-distance running has been examined in the context of a variety of parameters. However, there is scarcity of data regarding its effect on the vertical jump mechanics. The purpose of this study was to investigate the alterations of countermovement jump (CMJ) mechanics after a half-marathon mountain race. Twenty-seven runners performed CMJs before the race (Pre), immediately after the race (Post 1) and five minutes after Post 1 (Post 2). Instantaneous and ensemble-average analysis focused on jump height and, the maximum peaks and time-to-maximum peaks of: Displacement, vertical force (Fz), anterior-posterior force (Fx), Velocity and Power, in the eccentric (t_{ECC}) and concentric (t_{CON}) phase of the jump, respectively. Repeated measures ANOVAs were used for statistical analysis ($p \leq 0.05$). The jump height decrease was significant in Post 2 (-7.9%) but not in Post 1 (-4.1%). Fx and Velocity decreased significantly in both Post 1 (only in t_{ECC}) and Post 2 (both t_{ECC} and t_{CON}). A timing shift of the Fz peaks (earlier during t_{ECC} and later during t_{CON}) and altered relative peak times (only in t_{ECC}) were also observed. Ensemble-average analysis revealed several time intervals of significant post-race alterations and a timing shift in the Fz-Velocity loop. An overall trend of lowered post-race jump output and mechanics was characterised by altered jump timing, restricted anterior-posterior movement and altered force-velocity relations. The specificity of mountain running fatigue to eccentric muscle work, appears to be reflected in the different time order of the post-race reductions, with the eccentric phase reductions preceding those of the concentric one. Thus, those who engage in mountain running should particularly consider downhill training to optimise eccentric muscular action.

Key words: Countermovement jump, post-activation potentiation, force-velocity relationship, ensemble-average mechanics.

Introduction

Marathons and ultra-marathons attract the interest of researchers as excellent paradigms of challenging the limits of human performance (Millet and Millet, 2012; Vernillo et al., 2014). Mountain half-marathons are more popular with recreational runners (Running USA's Annual Half-Marathon Report, 2014), because they combine the challenge of long-distance running, while allowing runners to devote shorter periods in training and competing. The scarcity of data regarding the changes of muscle output following prolonged mountain running (Millet, 2011) makes the half-marathon an attractive intervention model for studying its fatiguing effects on vertical jump mechanics. This is due to the high running velocity and rate of energy expenditure associated with half-marathons (Saugy et al., 2013).

In previous long-distance road running studies (minimal inclinations) including post-running investigation of countermovement (CMJ) mechanics, the analysis was limited to jump height and the concentric phase of the jump (Lazzer et al., 2014; Lepers et al., 2000; Millet et al., 2000; Petersen et al., 2007). Considering the complexity of neuromuscular fatigue (Knicker et al., 2011), these studies may have underestimated the potential role of the eccentric phase of muscular action. However, eccentric musuclar action, in addition to constituting a fundamental component of the stretch-shortening cycle (Nicol et al., 2006), is also seen as a critical determinant of downhill mountain running performance (Millet, 2011). Much of the fatigue generated in prolonged mountain running is specific to eccentric muscle work (Millet, 2011; Temesi et al., 2014). This specificity is expected to reflect differently on the eccentric and concentric mechanics of a vertical jump after a race.

To date, CMJ analysis has focused on instantaneous mechanics and entire-curve profiles (i.e. ensemble averaging). Cormie et al. (2009; 2010) explored CMJ mechanics by examining peak displacement, force, velocity and power estimates, along with time-curve assessments. Gathercole et al. (2015) quantified fatigue-induced alterations in CMJ mechanics by estimating effect sizes, coefficients of variation or areas under force-velocity curves, whereas Gollhofer et al. (1992) and McBride et al. (2008) examined vertical displacement loops as alternate means of assessing typical work-energy potential. Given the scarcity of data regarding the potential alterations in the mechanics of jumping after long-distance mountain running, the purpose of this study was to examine the alterations induced in CMJ mechanics after a half-marathon mountain running race. The objective was to use instantaneous and ensemble-averaged curve mechanics to identify post-race alterations separately for the eccentric and the concentric phase of the vertical jump.

Methods

Participants

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The study organiser informed the participants (n = 27 men; Table 1) of the elements of the study. Prior to the race, the subjects provided informed consent and completed questionnaires on their health status and training history. The study adhered to the research policy of the National and Kapodistrian University of Athens.

Race characteristics

The race ('In the path of Deukalion', 7/12/2014, Parnassus Mountain, Delphi, Greece, http://www.deucalionrace.gr) began and completed outside the Museum of Delphi (544 m altitude, 15°C and 72% humidity). The altitude profile of the 23.5 km race distance (1018 m total positive elevation) (Figure 1), included an initial 5.2 km uphill (+11.3%), followed by 10.5 km of alternating downhill and uphill parts (1100, 1700, 1100, 1200, 1100 and 4300 m at ground slopes of –5.8, +4.9, –1.9, +12.4, -13.4 and +4.7%, respectively) and a final downhill of 8 km (–9.9%).

Testing procedures

Running speed, heart rate and perceived exertion

To assess the physiological effort of the runners during the race, running speed (km·hour^{-1}) and heart rate (HR) (beats·minute^{-1}) data were collected from 19 participants (Garmin Forerunner 310XT Garmin Ltd., 1 Hz sampling rate), uploaded to the Garmin Connect website (http://connect.garmin.com) and then averaged at every 100 m. The Garmin 310XT Forerunner relies on Global Positioning System (GPS) altimeter, with a GPS accuracy within ± 19 ft (equivalent to ± 5.7912 m) (Forerunner® 310XT owner's manual, 2013). It is a consistent commercial device with a 1.9% variability of the total elevation gain (the sum of the vertical distance travelled during uphills and downhills) (Menaspà et al. 2014). Also, each runner's perceived overall effort was assessed using the 6 to 20 Borg Scale.

CMJ testing and analysis

Vertical jump testing included CMJs performed on a force

Table 1. Characteristics of the participants (n=27 men)†.

	Mean (SD)	Range
Age (y)	41.3 (3.8)	22.9-57.8
Body height (m)	1.79 (.07)	1.62-1.93
Body mass (kg) †	80.1 (8.9)	61.4-101.7
Mountain racing experience (y)	5.6 (5.4)	1-19††
Finish time††† (h:m:s)	3:00:13 (0:35:18)	2:04:30- 4:11:30

† Pre-race value. †† 1yr: n=8, 2-5yrs: n=8, 6-8y: n=6, 10-15yrs: n=3, 19-20yrs: n=2
††† n=17 from 1st to 97th (2:04:18 to 3:10:42) and n=10 from 125th to 205th (3:18:12 to 4:11:18).

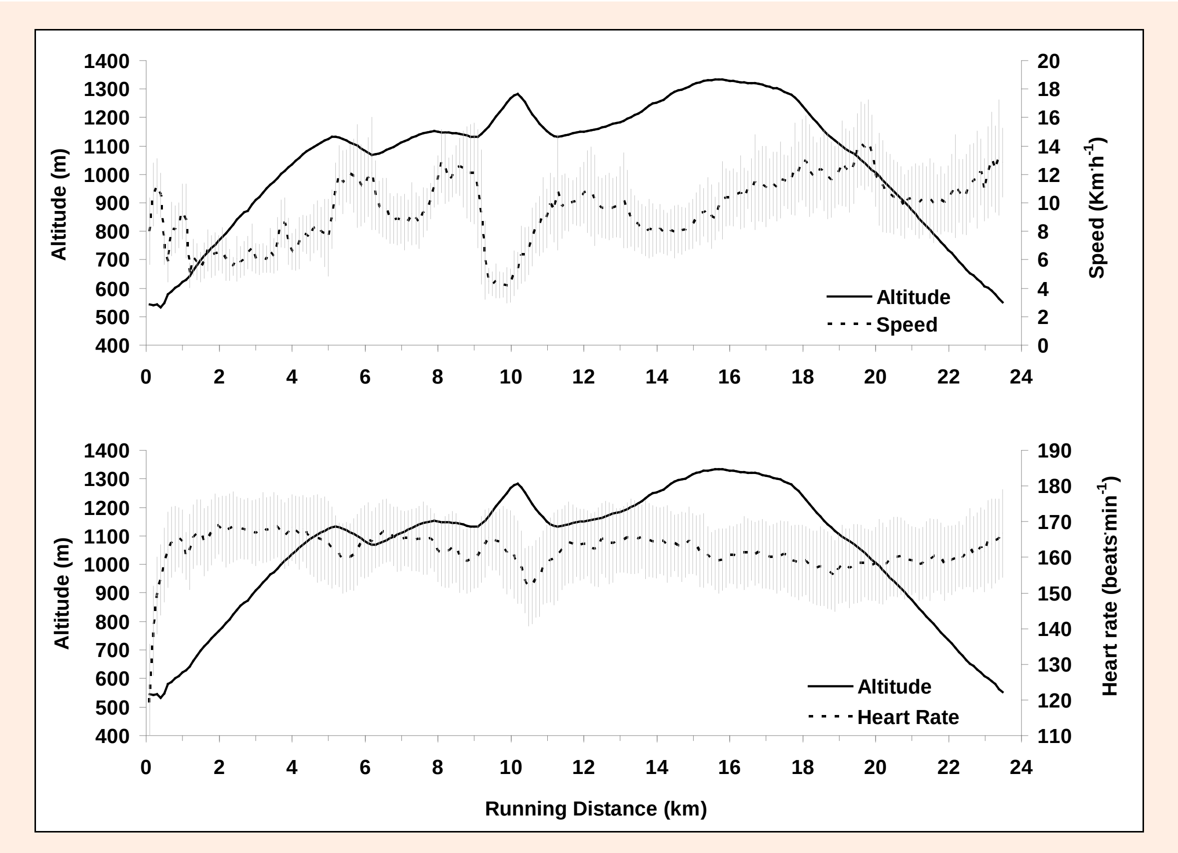

Figure 1. **The altitude profile of the half-marathon race (black solid line). Mean (black dotted line) and SD (grey vertical bars) of running speed (Km·h^{-1}) (top), and heart rate (beats/min) (bottom), superimposed on the altitude profile, for 19 of the 27 participants. Each running speed and heart rate value represents its average every 100 m of the running distance.**

plate positioned at a 50 m distance from the finish line (Kistler 9286AA, sampling rate at 750 Hz, Kistler BioWare® Data Acquisition and Analysis Software, version 3.2.6). The CMJ testing took place before the race (Pre: individual warm up of about 15–20 minutes) and at two time points after the race: immediately after (Post 1) and five minutes after Post 1 (Post 2). Due to the logistics of the testing protocol, the Post 1 and Post 2 time points varied among participants (Post 1: 4.50 ± 1.51 minutes; Post 2: 11.27 ± 1.51 minutes). Each participant performed three consecutive trials of their highest and most powerful CMJ (with their hands at mid waist) at Pre, Post 1 and Post 2, respectively. Between Post 1 and Post 2, the participants kept warm by wearing athletic garments and moving continuously. All CMJ trials were videotaped to allow for offline inspection of proper CMJ execution. The best trials (those with the greatest jump height) in Pre, Post 1 and Post 2, respectively, were used for further analysis. The durations of the eccentric phase (t_{ECC}) (from body weight baseline minus 4 standard deviations to maximum downwards displacement) and the concentric phase (t_{CON}) (from maximum downwards displacement to take-off) were expressed in absolute (s) and relative (percentage of total contact duration: % $t_{CONTACT}$), time units.

Instantaneous CMJ mechanics

The instantaneous CMJ mechanics for t_{ECC} and t_{CON} included the maximum peaks of Displacement, vertical force (Fz), anterior–posterior force, Velocity, and Power (Kistler BioWare® Data Acquisition and Analysis Software, version 3.2.6). Fz and Power were normalised to body weight due to its significant reduction (-2.4%) after the race (Pre race: 786.3 ± 87.9 N; Post race: 767.4 ± 84.7 N, p = 0.00). Time-to-maximum peaks estimates were derived for Displacement, Fz, Fx, Velocity and Power and, they were expressed in absolute (s) and relative (percentage of total contact duration: % $t_{CONTACT}$) time units.

Ensemble-averaged CMJ mechanics

The ensemble averaged time-curves (Displacement-time, Fz-time, Fx-time, Velocity-time and Power-time) were derived after resampling all individual CMJ trials (Cormie et al., 2009; 2010; Gathercole et al. 2015). Resampling was decided so that 400 time points represented the relative time from 0% to 100% of $t_{CONTACT}$. The number of 400 time points was based on the trial with the minimum $t_{CONTACT}$ (which was determined after inspecting all trials of Pre, Post 1 and Post 2, respectively). The resampled signals were used to normalise each individual time curve to $t_{CONTACT}$. In addition, the averaging of the ensemble curve for each participant (mean time curves) allowed for both entire and piecewise pre- to post-race curve comparisons. The averaged Displacement loops (Fz-, Fx-, Velocity- and Power-Displacement loops) (Gollhofer et al., 1992; McBride et al., 2008) and the averaged Fz-Velocity loops were plotted to compare the total loop areas (Cormie et al., 2009; 2010; Gathercole et al., 2015). In the case of multiple crossings between pre- and post-race curves, an additional comparison of the piecewise loop area was completed based on the time intervals defined by these loop crossings.

Statistical analysis

A series of one-way repeated measures ANOVAs were performed to identify the potential differences of the instantaneous CMJ mechanics among Pre, Post 1 and Post 2. In the case of a significant lack of sphericity (Mauchly's W), the ANOVA statistics were associated with proper correction of errors degrees of freedom with either the Greenhouse-Geisser or the Huynd-Feldt factor (ε) using $\varepsilon < 0.75$ or > 0.75, respectively. Significant F-tests were followed by three Bonferroni-adjusted pairwise comparisons ($\alpha = 0.01667$). The Cohen's d statistic was calculated to estimate the effect size (ES) for each pairwise difference. For each ensemble-averaged curve, the differences between Pre, Post 1 and Post 2 were tested for statistical significance using a series of repeated measures ANOVAs that were targeted to distinct intervals visually identified on each time curve or loop. To maintain the family-wise error rate for each interval of interest at the $\alpha_{FW} = 0.05$ level, each ANOVA was tested. A Bonferoni adjustment was applied to keep the per-comparison alpha level of $\alpha = 1-(1–0.05)^{1/k}$, with k representing the number of F-tests applied to each separate interval. Data are summarized and reported as means and standard deviations (SD). All statistical analyses were completed using the IBM SPSS 22.0 (Armonk, NY: IBM Corp.). Statistical significance was tested at a nominal family-wise error rate of $\alpha = 0.05$.

Results

Running speed, heart rate and perceived exertion

Running speed was estimated at 9.7 ± 2.3 km·hour^{-1} (range: 4.5 to 14 km·hour^{-1}) and heart rate at 163 ± 4 beats·minute^{-1} (range: 120 to 168 beats·minute^{-1}) (Figure 1). The perceived exertion reached 10.6 ± 2.6 units on the 6 to 20 Borg Scale.

CMJ testing

Jump height decreased after the race in both Post 1 and Post 2, but the difference was significant only in Post 2 ($p \le 0.05$) (Table 2). There were no significant post race differences in Displacement, neither in t_{ECC} nor in t_{CON} ($p > 0.05$) (Table 2). The absolute durations of $t_{CONTACT}$, t_{ECC} and t_{CON} did not change significantly (Table 2). The relative durations of t_{ECC} and t_{CON} also did not change significantly (t_{ECC}: 65.6 ± 2.8, 66.4 ± 3.4 and 65.4 ± 2.9% $t_{CONTACT}$, F = 1.56, p = 0.22, $\eta^2 = 0.06$ and t_{CON}: 34.4 ± 2.8%, 33.6 ± 3.4% and 34.6 ± 2.9% $t_{CONTACT}$, F = 1.56, p = 0.22, $\eta^2 = 0.06$, for Pre, Post 1 and Post 2, respectively).

Instantaneous CMJ mechanics

As shown in Table 2, significant Pre to Post 1 differences were found for Fx and Velocity in t_{ECC}, with significant Post 2 differences of Fx and Velocity, in both t_{ECC} and t_{CON}. Power in t_{CON} was the only variable displaying a significant difference in both Post 1 and Post 2. Regarding the absolute time variables, the only significant difference was identified in the late peak of Fz during t_{CON} in Post 1

Table 2. Mean (SD) of jump height and the dynamic variables during the eccentric (t_{ECC}) and the concentric (t_{CON}) contact phases, in Pre, Post 1 and Post 2. The statistics of the univariate repeated measures ANOVAs and the concomitant pairwise comparisons are also noted.

Variables	Mean (SD)			ANOVA			Pairwise Comparisons Cohen's d effect size (% of difference)		
	Pre	Post 1	Post 2	F	p value	η^2	Pre vs Post 1	Pre vs Post 2	Post 1 vs Post 2
Jump height (cm)	26.6 (4.7)	25.5 (4.7)	24.5 (4.6)	7.94	.00*	.23	.24 (-4.1)	.46* (-4.0)	.22* (-8.0)
DECC (cm)†	28.6 (5.3)	26.96 (6.5)	26.7 (5.8)	1.89	.18	.07	.28 (-5.9)	.33 (-1.0)	.04 (-6.8)
DCON (cm)†	37.7 (7.1)	37.08 (5.5)	36.19 (4.63)	1.18	.32	.04	.10 (-1.7)	.24 (-2.4)	.18 (-4.1)
FzECC (BW)	.53 (.14)	.51 (.20)	.56 (.17)	1.02	.36	.04	.12 (-3.8)	.18 (+9.8)	.27 (+5.7)
FzCON (BW)	1.27 (.24)	1.29 (.24)	1.26 (.30)	.30	.70	.01	.08 (1.6)	.04 (-2.3)	.11 (-0.8)
FxECC (N)	-91.4 (36.0)	-74.7 (42.4)	-70.3 (37.5)	8.35	.00*	.24	.43* (-18.3)	.55* (-5.9)	.11 (-23.1)
FxCON (N)	183.1 (48.2)	163.4 (51.8)	155.9 (41.5)	6.79	.00*	.21	.40 (-10.8)	.55* (-4.6)	.16 (-14.9)
VECC (m·s-1)††	1.01 (.16)	.90 (.20)	.95 (.19)	7.89	.00*	.23	.62* (-10.9)	.34* (+5.6)	.26 (-5.9)
VCON (m·s-1) ††	2.43 (.19)	2.38 (.19)	2.34 (.19)	10.02	.00*	.28	.27 (-2.1)	.48* (-1.7)	.21* (-3.7)
PECC1st (W·BW-1)†††	.33 (.13)	.30 (.18)	.34 (.19)	1.70	.25	.05	.19 (-9.1)	.06 (+13.3)	.22 (+3.0)
PECC2nd (W·BW-1)†††	-.48 (.20)	-.35 (.20)	-.39 (.22)	8.14	.54	0.24	.66 (-27.1)	.46 (+11.4)	.19 (-18.8)
PCON (W·BW-1)†††	2.04 (.47)	2.22 (.44)	2.13 (.45)	2.63	.04*	0.14	.40 (+8.8)	.20 (-4.1)	.21* (+4.4)

*significance of ANOVA and pairwise comparisons at $p \le 0.05$. † D = Displacement, †† V = Velocity, ††† P = Power
1st and 2nd: the 1st and 2nd, respectively, peaks of the Power–time curve during the eccentric contact phase.

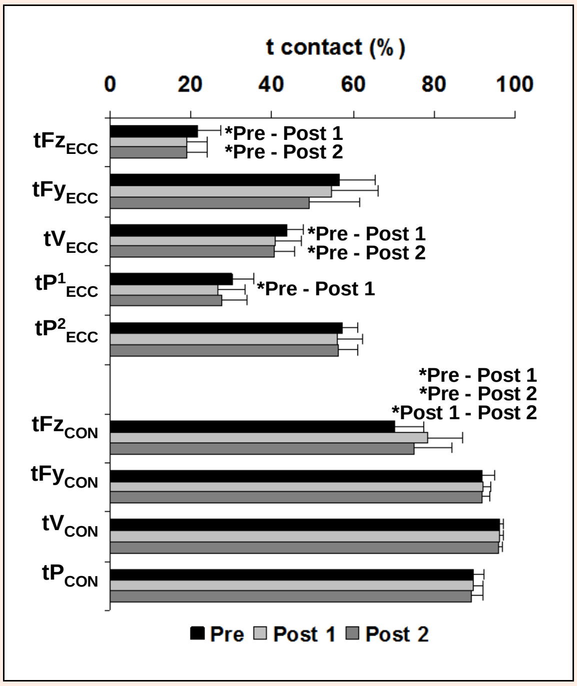

Figure 2. Mean (SD) of the relative time variables (% $t_{CONTACT}$) in the eccentric (ECC) and concentric (ECC) contact phases. The significant pairwise differences (* $p \le 0.05$) among Pre (black bars), Post 1 (light grey bars) and Post 2 (dark grey bars) are noted.

(Table 3). The relative time variables (Figure 2) indicate a significantly earlier time to peak the eccentric Fz in Post 2 (-2.8%) (Pre to Post 2, p = 0.05, ES = 0.48) and Velocity (Pre to Post 1: -3.2% earlier, p = 0.01, ES =0.60 and Pre to Post 2: = -3.3% earlier, p = 0.00, ES = 0.62). The relative times to peak the concentric Fz indicate a significantly delayed peak in Post 1 (+8.3%, p = 0.00, ES = 1.03) and in Post 2 (+4.9% later, p = 0.02, ES = 0.64), with Fz peaking significantly earlier in Post 2 than Post 1 (-3%, p = 0.02, ES = 0.35).

Ensemble-averaged time curves

Figure 3 depicts the ensemble-averaged time curves. Time intervals of significant reductions were identified for Fx (Pre to Post 1: 88.5–95.5%; Pre to Post 2: 59.8–67.8% and 89.8–94.2%), Velocity (Pre to Post 1: 41–58% and 75–90%; Pre to Post 2: 44.3–59% and 92.5–99%) and Power (Pre to Post 1: 33.4% and 55.8–62.5%; Pre to Post 2: 58.3–61.8%) (Figure. 3). Time intervals of significant increases and decreases were indentified for Fz (Pre to Post 1: 27–44.3%, 63–69.8% and 85–90%; Pre to Post 2: 88.8–91.3%) and Power (Pre to Post 1: 23–40.3% and 55.5–62.8%; Pre to Post 2: 23–40.3% and 58-62%) (Figure 3).

Ensemble-averaged displacement loops

There were no significant differences in the total loop area (Figure 4) of the Fz-Displacement loop (F = 0.84, p = 0.44, η^2 = 0.03), the Velocity-Displacement loop (F =

Table 3. Mean (SD) of the time variables during the eccentric (t_{ECC}) and the concentric (t_{CON}) contact phases, in Pre, Post 1 and Post 2. The statistics of the univariate repeated measures ANOVAs and the concomitant pairwise comparisons are also noted.

Variables	Mean (SD)			ANOVA			Pairwise Comparisons Cohen's d effect size (% of difference)		
	Pre	Post 1	Post 2	F	p value	η^2	Pre vs Post 1	Pre vs Post 2	Post 1 vs Post 2
tCONTACT (ms)	823 (112)	841 (169)	819 (148)	.33	.66	.01	.13 (+2.3)	.03 (-.4)	.14 (-2.6)
tECC (ms)	543 (89)	562 (133)	537 (108)	.64	.49	.02	.17 (+3.4)	.05 (-1.2)	.21 (-4.4)
tCON (ms)	280 (34)	279 (44)	282 (49)	.10	.86	.00	.03 (-.05)	.05 (+1.0)	.07 (+1.1)
tFzECC (ms)	182 (63)	162 (55)	153 (37)	4.25	.03*	.14	.34 (-11.2)	.50* (-16.3)	.20 (-5.7)
tFzCON (ms)	581 (115)	667 (186)	622 (163)	4.57	.02*	.15	.57* (+14.7)	.27 (7.1)	.26 (-6.6)
tFxECC (ms)	470 (114)	462 (157)	405 (130)	2.52	.09	.09	.06 (-1.6)	.48 (-13.7)	.40 (-12.3)
tFxCON (ms)	756 (116)	775 (170)	753 (149)	.33	.66	.03	.13 (+2.5)	.02 (-.4)	.14 (-2.8)
tVECC (ms)†	365 (73)	346 (97)	333 (65)	2.11	.13	.08	.23 (-5.2)	.38 (-8.7)	.16 (-3.7)
tVCON (ms)†	793 (111)	809 (167)	786 (146)	.33	.66	.01	.11 (2.0)	.05 (-.9)	.15 (-2.8)
tPECC1st (ms)††	253 (70)	228 (77)	221 (49)	2.60	.08	.09	.35 (-9.6)	.44 (-12.4)	.11 (-3.1)
tPECC2nd (ms)††	475 (86)	474 (120)	464 (108)	.14	.87	.01	.01 (-.1)	.11 (-2.2)	.09 (-2.1)
tPCON (ms)††	738 (115)	756 (170)	734 (150)	.31	.67	.01	.13 (+2.4)	.03 (-.5)	.14 (-2.8)

*significance of ANOVA and pairwise comparisons at $p \leq 0.05$. † V = Velocity, †† P = Power
1st and 2nd: the 1st and 2nd, respectively, peaks of the Power – time curve during the eccentric contact phase.

1.91, p = 0.16, η^2 = 0.07) and the Power-Displacement loop (F = 4.55, p = 0.02, η^2 = 0.19). The Fx-Displacement loop total area (Fig. 4) was significantly reduced after the race (F = 13.6, p = 0.00, η^2 = 0.29 with Pre to Post 1: p = 0.02, ES = 0.48, Pre to Post 2: p = 0.00, ES = 0.91 and Post 1 to Post 2: p = 0.00, ES = 0.51). The Fz- and Power-Displacement loops presented multiple crossings (Figure 4), with corresponding time intervals of significant post-race difference. In the Fz-Displacement loops, these time intervals were identified at 19.3–77% $t_{CONTACT}$ (p = 0.02) and at 77–94.8% $t_{CONTACT}$ (p = 0.00) for Pre compared to Post 1 and, at all time intervals for Pre compared to Post 2 (p = 0.00 for all). In the Power-Displacement loops, the time intervals associated with significant differences were indentified at 83.3–94.3% $t_{CONTACT}$ (p = 0.00) for Pre compared to Post 1 and, at 52.3–80.8% $t_{CONTACT}$ (p = 0.01) and 80.8–90.8% $t_{CONTACT}$ (p = 0.02) for Pre compared to Post 2.

Fz-Velocity loops

The Fz-Velocity loops presented multiple crossings (Figure 5), with corresponding time intervals of significant pre to post-race differences and reduced loop areas during t_{ECC} and early t_{CON} (Pre to Post 1: 19.3–78.3% $t_{CONTACT}$, p = 0.00, Pre to Post 2: 22.5–78.8% $t_{CONTACT}$, p = 0.00). The loop area increased towards the end of t_{CON} (Pre to Post 1: 94.5–100%, p = 0.00, Pre to Post 2: 22.5–78.8% $t_{CONTACT}$, p = 0.00).

Discussion

The main findings of the study were as follows: a) significant jump height reduction in Post 2 but not in Post 1, b) significant timing alterations in t_{ECC} as opposed to t_{CON}, c) altered timing in Fz_{CON} (though its magnitude did not change), d) a more pronounced peak magnitude alteration in Fx than in Fz (instantaneous mechanics and ensemble averaged curves) and e) force-velocity and force-length alterations, as indicated by the Fz-Velocity and Fz-Displacement loops, respectively.

The running speed (9.7 ± 2.3 km·hour^{-1}) cannot be compared with previous studies due the lack of mountain half-marathon data. The mean running speed of the present mountain half-marathon is higher than the mean speeds of 5.4 km·hour^{-1} (Temesi et al., 2014), 4.2 km·hour^{-1} (Morin et al., 2011) and 2.7 km·hour^{-1} (Vernillo et al., 2014), reported for ultra-marathons. Heart rate remained steady at a level of 90 ± 5% of the age-predicted maximum heart rate (HR_{MAX}), which was higher than that observed in longer mountain running distances (85 ± 3% HR_{MAX}, 95 km) (Lazzer et al., 2014) but similar to the one observed in shorter mountain distances (90 ± 4% HR_{MAX}, 15.6 km) (Easthope et al., 2014). Maintenance of a steady heart rate was accomplished by adjusting running speed to the ground slope (increasing in downhill slopes and decreasing in uphill slopes), which may be associated to the mechanism of pacing strategy regulation (Tucker and

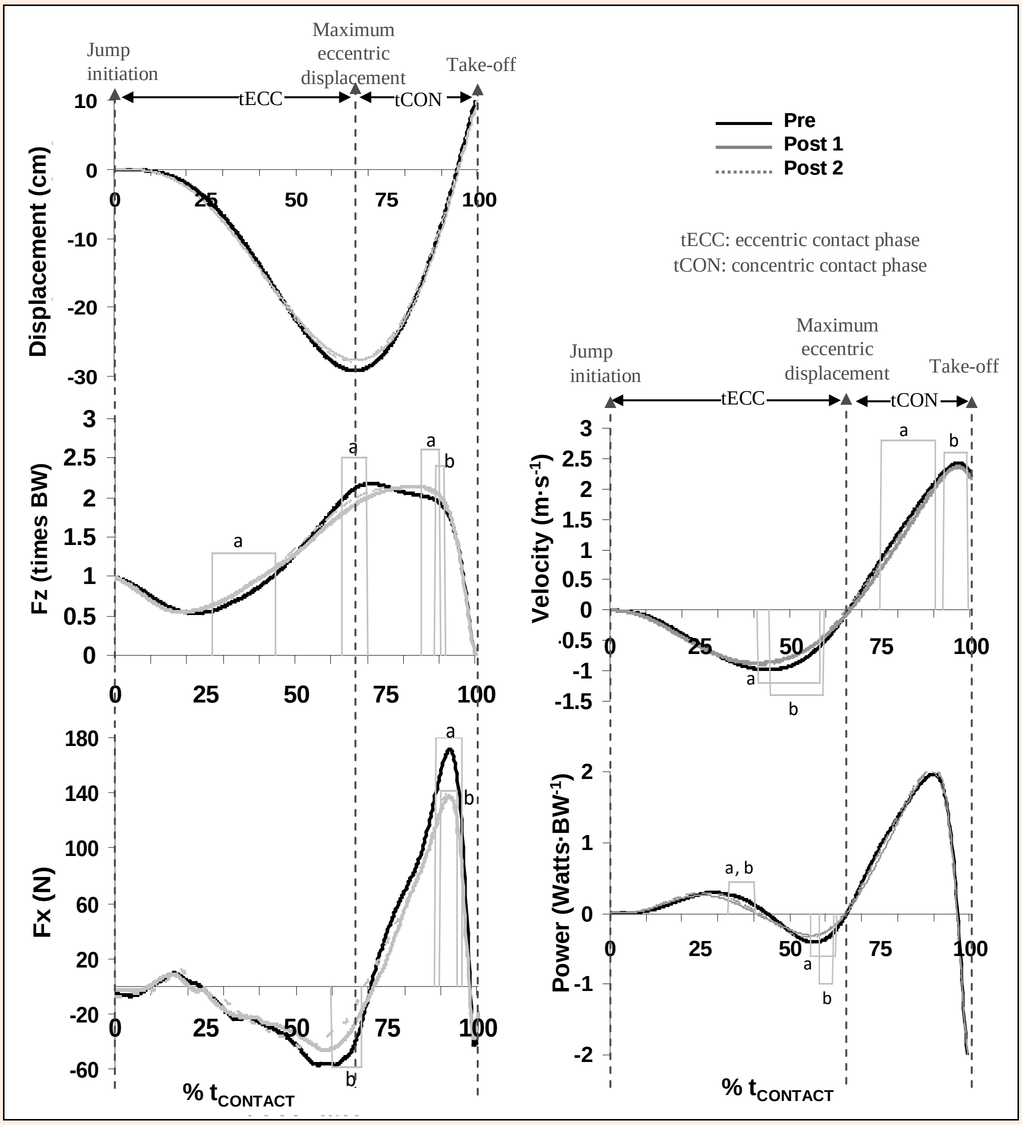

Figure 3. Time–curves: Displacement– (Right top), Fz– (Right center), Fx– (Right bottom), Velocity– (Left top) and Power– (Left bottom) time curves, in Pre (Black line), Post 1 (Solid grey line) and Post 2 (Dotted grey line), respectively. Time is expressed as a percentage of total contact duration (% $t_{CONTACT}$). The time intervals of significant Pre – Post 1 (a), Pre – Post 2 (b) and Post 1 – Post 2 (c) differences ($p \leq 0.05$) are noted.

Noakes, 2009). Along with their satisfaction of completing the race, the last 8 km downhill at 9.9% slope may explain the runners' perception of fatigue as medium because this slope approaches the metabolically optimal running grade and requires minimum energy expenditure (Snyder et al., 2012).

The decrease in post-race jump height was expected due to the functional alterations and the reduced maximal force-generating capacity induced by prolonged high-intensity running (Millet et al., 2002; Saugy et al., 2013; Vernillo et al., 2015). The jump height reductions in Post 1 (-4.1%, non significant) and Post 2 (-7.9%, significant) were smaller than the significant jump height decrease after a 65 km mountain ultra-marathon (-15.6%, Millet et al., 2000), a 28.4 km flat circuit (-10%, Lepers et al., 2000), as well as, the significant (-8.8%, Petersen et al., 2007) and non significant (-7%, Nicol et al., 1991) reduction after a road marathon.

The lack of significant jump height decrease in Post 1 may be associated with the counteraction of fatigue by the phenomenon of post-activation potentiation, as a result of the prolonged eccentric muscle actions during the last downhill part of the race (Hodgson et al., 2005; Tillin and Bishop, 2009). The existence of concurrent fatigue and potentiation has been previously reported after fatiguing endurance running, where the jump height was increased while, at the same time, the peak force was decreased (Boullosa et al., 2011). The mechanism is yet to be determined with regard to distance runners, however, the post-activation potentiation profile after fatiguing running exercises appears to be protocol dependent (Bullosa and Tuimil, 2009). Thus, in protocols inducing mechanical rather than metabolic fatigue due to high eccentric force requirements and relatively low energy demand, as the last downhill part of the present race, one could possibly argue for potentiation counteracting fatigue

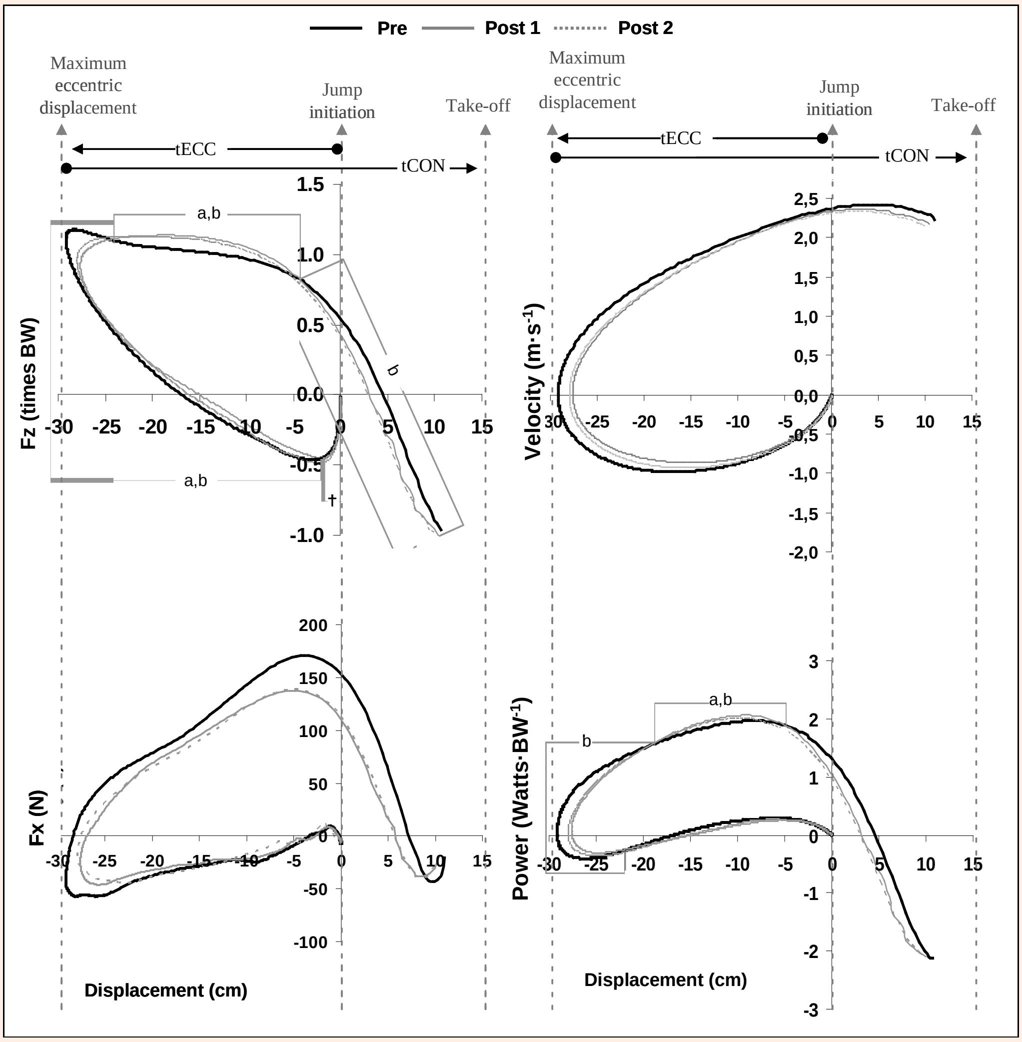

Figure 4. Displacement loops: Fz– (Right top), Fx– (Right bottom), Velocity–(Left top) and Power– (Left bottom) Displacement loops, in Pre (Black solid line), Post 1 (Solid grey line) and Post 2 (Dotted grey line), respectively. t_{ECC}: eccentric contact phase, t_{CON}: concentric contact phase. The time intervals of significant Pre – Post 1 (a) and Pre – Post 2 (b) piecewise loop area differences, due to multiple crossings in Fz– and Power–Displacement loops ($p \leq 0.05$) are noted.

(Bogdanis, 2012; Newham et al., 1987). In Post 1 of the present study, jump height was maintained despite the eccentric mechanics impairment, as those were denoted by the decrease of Fx (-18%) and Velocity (-11%), which might possibly be a mountain running dependence of potentiation profile. For certain, the association between fatigue, endurance running and post-activation potentiation cannot be substantiated in the present study; however, it constitutes an issue that warrants further investigation.

In studies investigating potential alterations of vertical jump performance, the anterio-posterior jump mechanics are not usually examined. Given the reduced jump height, the observed post-race Fx reduction cannot be explained as a more vertical jump but rather as the product of insufficient horizontal momentum that could, in turn, be converted into potential energy. The Fx-time curve denotes this reduction at time intervals that are critical for full bodyweight dynamic control, with the Fx-Displacement loop denoting a lowered workload throughout the total contact duration. A number of studies (Bobbert and Van Ingen Schenau, 1988; Bobbert et al., 2002; Fourchet_et al., 2012; Jones and Caldwell, 2003) suggest that muscle fatigue may affect the execution of the vertical jump with regard to the anterior-posterior direction of the movement. For instance, forward movement may be restricted, meaning that the fatigued hip extensors avoid configurations requiring strong posterior acceleration (Bobbert and Van Ingen Schenau, 1988; Jones and Caldwell, 2003). Similarly, the fatigued tibialis anterior restricts the forward movement of the body to prevent the requirement for posterior acceleration and to align the ground reaction force line of action with the centre of pressure (Bobbert and Van Ingen Schenau, 1988; Jones and Caldwell, 2003). The fatigued plantar flexors may also restrict foot rotation (Bobbert et al., 2002) and the forward movement of the centre of pressure along the base of the foot (Jones and Caldwell, 2003). In mountain distance running, plantar flexors become more fatigued compared to dorsi flexors (Fourchet_et al., 2012). This imbalance may prevent alignment of the ground reaction force with the centre of pressure. The variable terrain of a mountain race may increase muscle fatigue through unpredicted and continuously changing postural control requirements (Degache et al., 2014), a condition that may partially account for the significant alterations of the anterior-posterior component of the ground reaction force.

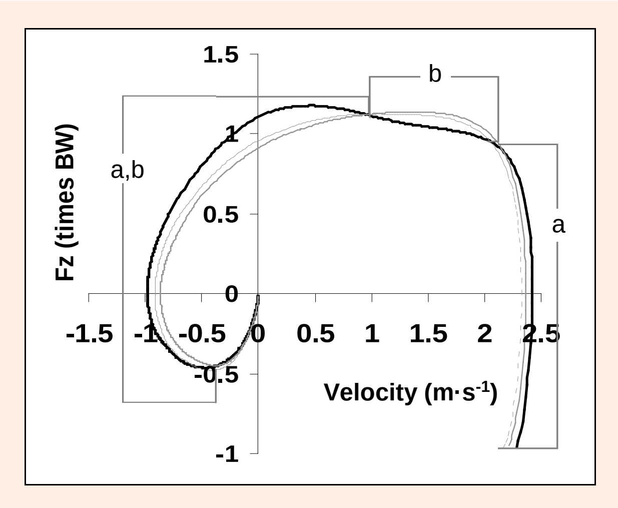

Figure 5. Force-velocity loops, in Pre (Black solid line), Post 1 (Grey solid line) and Post 2 (Grey dotted line). No significant difference in the total loop area ($p \leq 0.05$). The time intervals of significant Pre-Post 1 (a) and Pre-Post 2 (b) piecewise loop area differences due to multiple crossings are noted.

The alteration in the timing of the jump variables is of particular importance. The limited studies on CMJ performance after mountain running do not provide timing data. In a road marathon study, a decrease in CMJ height (-8.8%) was accompanied with an almost triple increase of eccentric (+21%) over total (+7.3%) contact phase (Petersen et al., 2007). A short eccentric phase is a prerequisite for stretch-induced force enhancement, increased conservation of elastic energy (Saunders et al., 2004) and greater force potentiation (Van Ingen Schenau et al., 1997).

Despite the decrease in jump height, the fatigued jumps of the present study were performed with the same relative timing of total contact duration, which is in agreement with previous studies reporting insignificant changes of the eccentric and concentric contact phases in fatigued CMJs (Rodacki et al., 2002). However, a robust template motor program irrespective of fatigue (Rodacki et al., 2002) cannot be completely implemented, due to the altered relative timing of the variables within the time limits of the eccentric and the concentric jump phases. A problem when individuals execute vertical jumps is the efficient transfer of the trunk and lower body rotational energies into the maximum vertical take-off velocity (Bobbert and Van Ingen Schenau, 1988). For the production of the required rotational energy under fatigued conditions, it is critical that the changes of motor template still allow for an optimal timing of segmental displacement. A timing alteration may influence vertical jump performance by disrupting the time difference between the segmental acceleration maxima (Hochmuth, 1975). Timing alteration may also decrease the sharpness in the activation of the muscles, leading to poor use of mechanical energy and increased metabolic energy in the completion of the movement (Luhtanen and Komi, 1978). The earlier timing of Fx, Velocity and Power whithin t_{ECC}, highlights the altered timing pattern during the eccentric phase of the jump, which most likely reflects an increased passive muscle stiffness (Ishikawa et al., 2006), triggering an earlier decrease in the body's gravitational descent. The later timing of Fz within the concentric phase of the jump may be attributed to reduced strength (Cormie et al., 2009) or lower eccentric velocity (Harman et al., 1990). Of particular interest is the opposite direction in the altered timing of Fz during t_{ECC} (earlier in $t_{CONTACT}$) and during t_{CON} (later in $t_{CONTACT}$). The expansion of the time interval defined by the Fz peaks in t_{ECC} and t_{CON} is most possibly associated with the delay between the eccentric and the concentric muscle actions, clarifying a fatigued stretch-shortening cycle (Nicol et al., 2006). This relative time expansion also shows an altered force-velocity relation, as depicted in the Fz-Velocity loop (Fig. 5), which results from the change in the timing rather than the magnitude of the produced vertical force. An altered force-length relationship is most likely indicated in the modified Fz-Displacement loop, probably due to the downhill sections of the race that impose a prolonged workload on the knee extensors over a greater muscle length (Mizrahi et al., 2001).

The coexisting alterations in the Fz-Velocity and the Fz-Displacent loops denote that half-marathon mountain running induces fundamental changes in the vertical jump muscle mechanics. These changes lead to lower post-race jump height, while at the same time, a greater workload (Fz-Displacement loop) and greater power (Power-Displacement loop) are produced during the late part of the concentric phase, where the body must return to the initial position of zero displacement. Considering that peak velocity in the eccentric phase of the CMJ also decreases post-race, the observed alterations in the Fz-Velocity and Fz-Displacement loops may also be associated with lower acceleration levels at the beginning of, and throughout the concentric phase of the jump (Cormie et al., 2009).

Conclusion

The CMJ mechanics were significantly altered following the half-marathon mountain running race, with a significant jump height reduction in Post 2 but not in Post 1. The post race fatigued CMJ mechanics were characterised by altered jump timing, restricted anterior-posterior movement and altered force-velocity relations, that may denote a disrupted energy transformation from rotational to potential. The specificity of mountain running fatigue to eccentric muscle work, is most likely highlighted in the different time order of the post-race reductions, where the eccentric phase reductions preceded those of the concentric one. Thus, those who engage in mountain running should particularly consider downhill training to optimise eccentric muscular action.

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Key points

- The 4.1% reduction of jump height immediately after the race is not statistically significant
- The eccentric phase alterations of jump mechanics precede those of the concentric ones.
- Force-velocity alterations present a timing shift rather than a change in force or velocity magnitude.

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