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RESEARCH

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Continuous vertical jump test is a reliable alternative to wingate anaerobic test and isokinetic fatigue tests in evaluation of muscular fatigue resistance in endurance runners

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Abstract

Background Endurance athletes face the challenge of sustaining performance while managing cumulative fatigue during half marathons and ultra-marathons while the evaluation of muscular fatigue resistance in endurance runners is essential to optimize training and race-day performance. This study aimed to assess the validity of total work measured during the continuous vertical jump test (CVJT) as an alternative to Wingate anaerobic power test (WAnT) and isokinetic fatigue test (ISO FAT) for evaluating muscular fatigue resistance and to test whether these measures correlated to race performance during half marathon (HM) and ultra marathon (UM) races.

Methods Twenty-two male recreational distance runners (age: 35.23 ± 21.12 years, height: 171.13 ± 21.35 cm, weight: 69.49 ± 11.25 kg) were recruited in this study. Anthropometrics, WAnT, ISO FAT, and CVJT were interspersed 24 h of recovery, within 7 weeks.

Results Total work during WAnT was highly associated with the measures of ISO FAT and CVJT both pre-race and post-race conditions ($p < 0.001$). Bland Altman limits of agreement (LOA) revealed that total work measures of ISO FAT and CVJT both during baseline and following HM and UM races (Hedge's g: 0.411; 0.353; 0.428; 0.435) were lower than WAnT while their 95% LOA represented 23.46%, 32.81%, 35.02%, and 36.79% of WAnT, respectively.

Conclusion Strong internal consistency and reproducibility in total work measures and the magnitude of the difference among tests suggests that CVJT, WAnT, and ISO FAT warrant interchangeability in assessing muscular fatigue resistance. These findings offer important implications and highlight the utility and feasibility of CVJT as an alternative to WAnT and ISO FAT for training load assessment.

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Keywords Isokinetic fatigue test, Wingate anaerobic test, Continuous vertical jump test, Half-marathon, And ultra-marathon

Introduction

In endurance sports such as half marathons (HM) and ultra-marathons (UM), athletes are required to maintain high levels of performance over extended periods, often while managing the cumulative effects of fatigue [1, 2]. Muscle fatigue is a critical factor influencing performance during endurance races, and its evaluation can provide insight into the physiological demands placed on the body at different intensities and distances [3]. Evaluating the muscular fatigue resistance induced by the distance and intensity of a race is important for optimizing training and improving running performance in endurance runners [4].

Evaluation of muscular fatigue resistance plays a vital role in endurance events like half marathons and ultra-marathons, where sustained muscular endurance is essential for maintaining efficiency over long distances [5]. Runners with better muscular fatigue resistance can delay the onset of fatigue, thereby preserving performance and reducing the risk of injury [6]. As endurance athletes push through prolonged physical exertion, the ability to resist muscular fatigue plays a significant role in maintaining optimal pacing and minimizing early muscle breakdown. Research has shown that runners with higher muscular endurance can sustain a higher proportion of their maximal force output over extended periods, which is crucial during the late stages of a race when fatigue becomes more pronounced [7]. Additionally, muscular fatigue resistance helps reduce the risk of injury by preserving proper running mechanics, preventing the compensatory movements that often occur when muscles become overly fatigued [8]. Furthermore, studies have demonstrated that training aimed at improving muscular endurance can enhance performance in ultra-endurance events by increasing the time to exhaustion and decreasing the perceived effort [9]. Thus, optimizing muscular fatigue resistance is essential for achieving peak performance in endurance running. Various testing methods are used to evaluate muscular fatigue resistance, including the Wingate Anaerobic Test (WAnT), the isokinetic fatigue test (ISO FAT), and the Continuous Vertical Jump (CVJ) test. The WAnT, isokinetic fatigue test, and continuous vertical jump test provide valuable insights into different aspects of muscular endurance, with each test measuring fatigue resistance in unique ways [10]. The WAnT is valuable for assessing anaerobic capacity and power, highlighting fatigue resistance at high intensities [11]. The isokinetic fatigue test evaluates muscle strength and endurance under controlled conditions, providing insight into how muscles perform under repetitive stress [12, 13]. The CVJT test, on the other hand, measures neuromuscular fatigue by analyzing jump height in repeated efforts [14]. While these tests provide complementary information, their interchangeable use in assessing muscular fatigue resistance in endurance athletes remains debated. The WAnT is more specific to short-burst fatigue, while the isokinetic test provides more comprehensive data on overall muscle endurance. The CVJT test offers a practical measure of endurance-related fatigue in a field setting [15]. While they each measure different aspects of muscular endurance, using these tests in combination can offer a more complete evaluation of fatigue resistance in endurance runners [16].

However, even though these tests measure different aspects of muscular performance and can help assess endurance, strength, and fatigue, the question of whether these results are interchangeable depends on how well these tests match the demands of long-distance running events [17–19]. Furthermore, little is known about the fatiguing effects of prolonged road running on the continuous vertical jump mechanics and the changes of muscle output since the previous analysis was limited to jump height and the concentric phase of the jump in previous long-distance road running studies [20, 21].

To the best of our knowledge, this is the first study that examines whether the measures of total work output during CVJT both during non-fatigued and fatigued conditions are in agreement as determined by the WAnT and ISO FAT and could be used interchangeably in assessment of muscular fatigue resistance in endurance runners. Thus, the purpose of this study was to assess the validity of total work (TW) measured during the CVJT before and after HM and UM races to test the reproducibility of the data under non-fatigued and fatigued conditions and compare TW outputs obtained from these three different testing modalities. A secondary aim was to determine whether CVJT could be used interchangeably with TW measured during WAnT and ISO FAT for evaluating muscular fatigue resistance and to test whether these measures correlated with race performance during HM and UM races. With this in mind, we hypothesized that (a) consistent with differences in the total distances covered between HM and UM, the total work output values of the runners would decrease progressively with increasing running distance, duration, differences in pacing strategy (b) the total work output, as a response to the total distance covered following UM would be greater than those observed in HM, (c) due to the nature of these running events, total work output during CVJT following

HM and UM races would be lower compared to baseline measures as a result of fatigue-induced height loss.

Methods

Participants

The participants were recruited based on the following inclusion criteria: (a) must be a healthy male endurance runner between the ages of 25–36, and (b) have participated in endurance training and marathon races over the last 5 years. Participants who have had any musculoskeletal injury in the past 6 months that may influence neuromuscular performance were excluded from the study. Since we examined the neuromuscular components of the participants to assess the extent of exercise-induced decreases in total work capacity as a response to the races with shorter versus longer distances we only included runners competing at both HM and UM within the same calendar year. Participants who were competing in only HM or UM races were not included in this study.

Immediately before testing sessions, all participants completed a Physical Activity Readiness Questionnaire (Par-Q+) to assess whether runners competing in different race distances present differences in training background and habits according to the distance of preference. Individual height and weight were also measured in this session. Twenty-two, healthy male endurance runners (age: 35.23 ± 21.12 years, height: 171.13 ± 21.35 cm, body weight: 69.49 ± 11.25 kg, percent fat mass: 21.17 ± 10.32%) without prior history of knee injury volunteered to participate in this study, respectively. All participants were informed about the purpose, content, and potential risks and benefits of the study, and signed an informed consent.

Study design

The protocol was approved by the Mersin University Institutional Review Board under the Declaration of Helsinki for human research (Date of approval: 10/17/2022; Protocol number: 2022-043). Before the study, three WAnT, ISO FAT, and CVJT trials were recorded for the methods' validity. The participants visited the laboratory a total of 4 times, consisting of one familiarization visit for concurrent validity of measures, and three actual test visits. The familiarization visit was to minimize potential learning effects. Anthropometric parameters were also measured during this session. The study was carried out in six different experimental phases conducted in two different cities with two different running races. During the race, participants used a timing chip to calculate the net time to go from the starting line of the race to the finish line. Race time was also measured at 5-km intervals during the race. Heart rate parameters of the participants were measured using a Polar H10 sensor chest strap device throughout the HM and UM races (Polar Electro Oy, Kempele, Finland; sampling rate: 1000 Hz; app software: Elite HRV App, Version 5.5.1). All the runners participated in a half-marathon race and an ultra-marathon race and performed the same laboratory tests. To avoid any residual fatigue induced by a recent workout, participants were asked to refrain from strenuous exercise 48 h before the tests.

During the first visit, participants were informed of the overall experimental protocol, potential risks, and the purpose of the study. After completing a written consent form, participants were familiarized with continuous vertical jump tests. Baseline anthropometric measures and CVJT, ISO FAT, and WAnT tests were administered to all the participants by the same investigator. They were separated by at least 24 h of recovery, within 7 weeks. Participants were instructed to maintain their regular diet during the participation period and were asked to refrain from strenuous exercise, alcohol, and caffeine consumption during the 24 h preceding these visits (Fig. 1).

Upon completion of baseline measures, all participants completed a half-marathon race and an ultra-marathon race with 6-week intervals between the two races. CVJT was also performed by all participants after the half-marathon and ultra-marathon races. The participants were informed of the objectives, practical details, and possible risks associated with the experiment, and signed a written informed consent to participate in the study.

Procedures

Wingate anaerobic test (WAnT)

WAnT test was performed on a Monark 864 electromagnetically braked cycle ergometer (Varberg, Sweden) with automatic toe strap pedals that allow the participant to develop maximum power during the whole revolution. Before the test session, seat height was adjusted to each participant's satisfaction, and clips with straps were used to prevent the feet from slipping off the pedals. Each participant cycled for 30 s against constant resistance in the seated position. All participants performed a standardized warm-up, which consisted of a 7-min warm-up period at 100 W with a cadence of around 100 rpm followed by a set of 3 sprints of 6 s at 0.7, 0.8, and 0.9 $Nm \cdot kg^{-1}$ of body mass, interspersed by 54 s of passive recovery. Upon completion of warm-up, a 5-minute rest period was given to each participant before they started pedaling to determine the maximum workload at which peak power output elicits. This phase of the test consisted of several 6-second sprints against increasing load, interspersed with 5-minute periods of recovery where initial resistance was set at 0.9 $Nm \cdot kg^{-1}$ and increased by 0.1 $Nm \cdot kg^{-1}$ until power output decreased during two consecutive sprints. The highest power output observed during the test was considered peak power output. After a 10-minute rest period, this workload was used during the

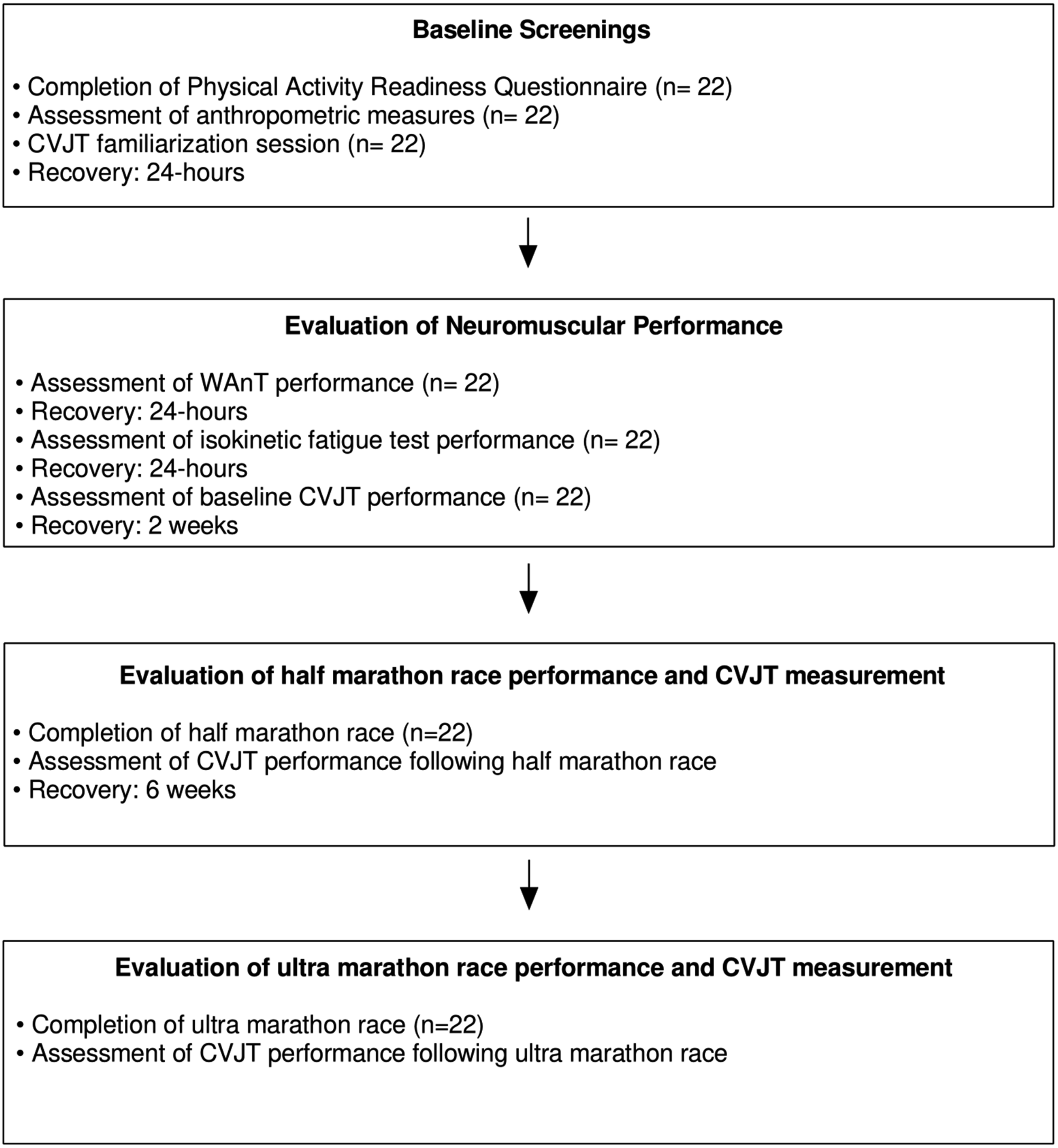

Fig. 1 Schematic representation of the experimental

standard WAnT protocol to measure muscular fatigue resistance of participants. Before the actual test following the warm-up session, the participants started cycling at 60 RPM for approximately 10 s with no weight. Following the signal of the administrator, the administrator lowered the test weight basket and the resistance load was introduced in the initial seconds of the test. Mean power output over the test was computed and converted into cumulated total work by multiplying it by 30 to determine the total work performed during the WAnT, which was considered as the reference measure for total work (TW WAnT, in J).

Isokinetic fatigue test

The following test visit was completed with at least a 24-hour separation. Isokinetic knee extensor (con) and flexor (con) muscle strength performance were evaluated using a HUMAC NORM Isokinetic dynamometer (CSMI, USA). At the same time, the participants were seated in an upright position with their hips flexed at an angle of 90°. Participants had their meals at least 3 h before the next exhaustive exercise. Before testing, all participants received the instruction to perform a full range of motion during each contraction and to push up and pull down until they met the stop provided by the isokinetic device.

Familiarization with the dynamometer and the setup included ten submaximal and progressively intensified concentric contractions (extension and flexion) at an angular velocity of 120°/s. During the test, the hips and thighs of participants were stabilized through pelvic and thigh straps. The range of motion was 100° (0° corresponding to a full active extension). After a 2-minute pause, participants were asked to perform 3 submaximal reciprocal concentric contractions at an angular velocity of 180°/s. Afterward, they performed 30 consecutive maximal reciprocal concentric contractions at an angular velocity of 180°/s. Participants were encouraged to push/pull as hard and fast as possible and complete the full range of motion. The participants were asked to perform these repetitions as quickly as possible and at a maximal effort. They were also told to grasp the handles at the sides of the chair throughout the warm-up and the test. Strong verbal encouragement was given throughout the trial to motivate participants to develop maximal contraction during each repetition. Total work (J), which has shown to be very highly reliable for knee extensors (ICC = 0.91) and highly reliable for knee flexors (ICC = 0.75), was computed during the entire range of motion of each repetition using the device's software and summed to obtain total work (TW ISO FAT, in J) [22]. Gravity correction was implemented before the isokinetic test protocol session. During all isokinetic testing sessions, the participants underwent the same protocol for both legs. Total work during the ISO FAT was determined as the sum of the knee extension and flexion moments of both limbs during 30 consecutive maximal reciprocal concentric contractions.

Evaluation of muscular fatigue resistance using a continuous vertical jump test protocol

Total work output during CVJT both before and after HM and UM races was measured using a protocol developed and tested by Ha et al., (2020) with a lower frequency of 12 jumps/min [23]. During the baseline CVJT session, participants performed a total of 3 sets of 30 consecutive maximal vertical jumps from a 90° knee joint angle with a 5-minute recovery period following each set. During each set, participants jumped with the instruction of a metronome sound with a cadence of 12 jumps/min, such that the total exercise time of each set took 150 s. The subjects were instructed to jump "as high as possible" during the test. After the first and the second set of vertical jump exercises, participants rested in the chair for 5 min. During the testing, the participants were instructed to avoid any countermovement in this position to eliminate the utilization of elastic energy. The duration of the jump was measured as an index of jump height by digital vertical jump equipment (TKK-5414, TAKEI, Japan). During the CVJT, participants crossed both arms and placed their hands on their shoulders to minimize the effects of the arm swing. Participants were not allowed to see their jump height record on the equipment's screen to minimize the feedback effect. Since the jump height and total work measured during each set of the vertical jump test during baseline measurements revealed no statistically significant differences between the sets, the participants performed the same test procedure with 1 set of 30 consecutive maximal vertical jumps immediately after the half-marathon and ultra-marathon races. The cumulative jump height of these thirty jumps was recorded for further analysis to estimate total work output ($TW_{baseline}$, $TW_{half\text{-}marathon}$, and $TW_{ultra\text{-}marathon}$, in J).

$$Jump\ height\ (cm) = \frac{flight\ time\ (cm)^2 \times gravitational\ acceleration\ \left(9.81\ m/s^2\right)}{8}$$

Total work during 30 consecutive CVJT (J) = 21.2 * cumulative jump height (cm) + 23.0 body mass (kg) – 1.393.

Statistical analyses

Descriptive statistics were used to summarize the data and the results were expressed as mean ± standard deviation. Normal Gaussian distribution of the data was verified by the Shapiro-Wilk test, and homoscedasticity by a modified Levene Test. All variables met these underlying hypotheses. A repeated measures ANOVA test was conducted to compare the effect of three sets of 30 consecutive vertical jumps on average and cumulative jump height, and TW measured between each set during baseline screenings. Additionally, a repeated measures ANOVA was conducted to assess the differences in total work output across five conditions: WAnT, ISO FAT, CVJT-B, CVJT-HM, and CVJT-UM. A paired t-test was used to test the null hypothesis that there were no differences in TW parameters measured during WAnT, ISO FAT, CVJT-B, CVJT-HM, and CVJT-UM. Pearson's (r) correlation was used for concurrent validity and Cronbach's alpha (α) was used to estimate the internal consistency of the TW measured during WAnT, ISO FAT, and CVJT sessions. The interactions between race performance and total work output measured during

Table 1 Physiological parameters of the participants

Variables	Mean ± S.D.
Age (years)	35.23 ± 21.12
Height (cm)	171.13 ± 21.35
Body weight (kg)	69.49 ± 11.25
Percent fat mass (%)	21.17 ± 10.32
VO_{2max} (ml.kg.min^{-1})	58.36 ± 2.58
Average training distance/week before HM (km)	37.03 ± 13.41
Average training distance/week before UM (km)	55.24 ± 10.07
Marathon racing experience (years)	6.03 ± 3.41
Half-marathon finish time (h: m:s)	1:32:01 ± 0.07
Half-marathon heart rate (beats.min^{-1})	182.9 ± 5.44
Half-marathon running speed (km·h^{-1})	13.70 ± 1.23
Ultra-marathon finish time (h: m:s)	5:82:35 ± 2.38
Ultra-marathon heart rate (beats.min^{-1})	174.70 ± 5.25
Ultra-marathon running speed (km·h^{-1})	7.85 ± 1.291

Note. Data are presented as mean and standard deviation. (h: m:s): hours: minutes: seconds

CVJT following both HM and UM races were analyzed using Pearson correlation coefficient. When Pearson correlation coefficients and ICC values reached significance, the strength of the correlations was classified, as follows: very low = 0–0.25; low = 0.26–0.49; moderate = 0.50–0.69; high = 0.70–0.89; and very high = 0.90–1.00.

Bland-Altman analysis was used to determine the absolute lower and upper limits of agreement (LOA). Lower and upper LOA between predicted and actual TW measures were determined as follows: Lower LOA = Mean of difference – (1.96 × SD of Difference); Upper LOA = Mean of difference + (1.96 × SD of Difference. The Hedge's g (g) assessed the difference's magnitude. The magnitude of the difference was considered either small ($0.2 < g \leq 0.5$), moderate ($0.5 < g \leq 0.8$), or large ($g > 0.8$). The systematic error (bias) was also determined to visualize the mean difference between the paired comparisons. Test-retest reliability for TW measures were quantified using the intraclass correlation coefficient (ICC) and the standard error of measurement (SEM) [24]. Statistical significance was set at $p < 0.05$. SPSS + version 17.0 statistical software was used (SPSS, Inc., Chicago, IL). GraphPad Software GraphPad Prism 6 was used for graphical expression.

Results

The data relating to the anthropometric characteristics of the participants are presented as Mean ± SD (Table 1).

TW measured during WAnT was 38.623 ± 12.664 J. TW accumulated during ISO FAT, $CVJT_{baseline}$, $CVJT_{half}$, and $CVJT_{ultra}$, and their comparison with WAnT is presented in Table 2.

There was no significant effect of the number of sets on average jump height [F (2, 63)] = 0.008, $p = 0.992$] and TW [F (2, 63)] = 0.183, $p = 0.833$] for the three test conditions at the baseline measures. Similarly, a repeated measures ANOVA was conducted to assess the differences in total work output across five conditions: WAnT, ISO FAT, CVJT-B, CVJT-HM, and CVJT-UM (Fig. 2). The assumption of sphericity was not met, as indicated by the Geisser-Greenhouse epsilon value of 0.3823. Therefore, the results were interpreted using the Greenhouse-Geisser correction. The repeated measures ANOVA showed no significant difference in total work output between the five conditions, F (1.529, 32.11) = 0.1335, $p = 0.8201$, with a small effect size (R^2 = 0.0063). This indicates that, overall, the different treatments did not have a statistically significant effect on the total work output. However, individual differences accounted for a significant portion of the variance in total work output, highlighting the substantial role of participant variability in the outcome (R^2 = 0.9639).

The distribution of the TW parameters measured during WAnT, ISO FAT, and CVJT sessions had no serious ceiling and floor effects. The results of the internal consistency calculations for TW of these three testing conditions produced a very high alpha value of 0.94, 0.92, and 0.90, respectively. The Pearson product-moment correlation coefficient showed a very high correlation between the test–retest measurements for all testing conditions ($p < 0.01$). The results of Pearson product-moment correlation revealed that TW measured during the ISO FAT was highly associated with TW measured during the WAnT (Fig. 3a; ICC: 0.860, SEM: 2879, MDC_{95}: 7972.25, $p < 0.0001$). Similarly, TW measured during the baseline CVJT was positively significantly correlated with TW

Table 2 Comparison of total work output (TW) measured during the high-intensity isokinetic fatigue test (ISO FAT), during baseline vertical jump test ($CVJT_{baseline}$), and following half ($CVJT_{half}$) and ultra-marathon ($CVJT_{ultra}$) race with TW measured during the wingate anaerobic test (WAnT; 38623 ± 12664 J)

Variables	Difference with Total WAnT Work (J)	*p*	Magnitude of the difference (Hedge's g) [b]	95% LOA [c]	ICC	95% CI (Lower, Upper Bound)	SEM	MDC_{95}
TW ISO FAT (J)	-5398	0.769 [a]	0.411	23.46	0.860	0.378 - 0.901	2879	7972.25
TW $CVJT_{baseline}$ (J)	-4515	0.840 [a]	0.353	32.81	0.883	0.644 - 0.956	2637	7302.34
TW $CVJT_{half}$ (J)	-4814	0.702 [a]	0.428	35.02	0.847	0.517 - 0.943	2703	7490.54
TW $CVJT_{ultra}$ (J)	-4895	0.622 [a]	0.435	36.79	0.842	0.503 - 0.941	2735	7553.70

Note. [a] comparison to the TW measured during the Wingate anaerobic test ($p > 0.05$); [b] the magnitude of the difference was considered either small ($0.2 < g \leq 0.5$), moderate ($0.5 < g \leq 0.8$), or large ($g > 0.8$). [c] expressed in percentage of TW measured during WAnT, ICC, intraclass correlation coefficient; CI, confidence interval; LOA, limits of agreement; SEM, standard error of measurement, MDC_{95}, minimum detectable change at the 95% confidence interval

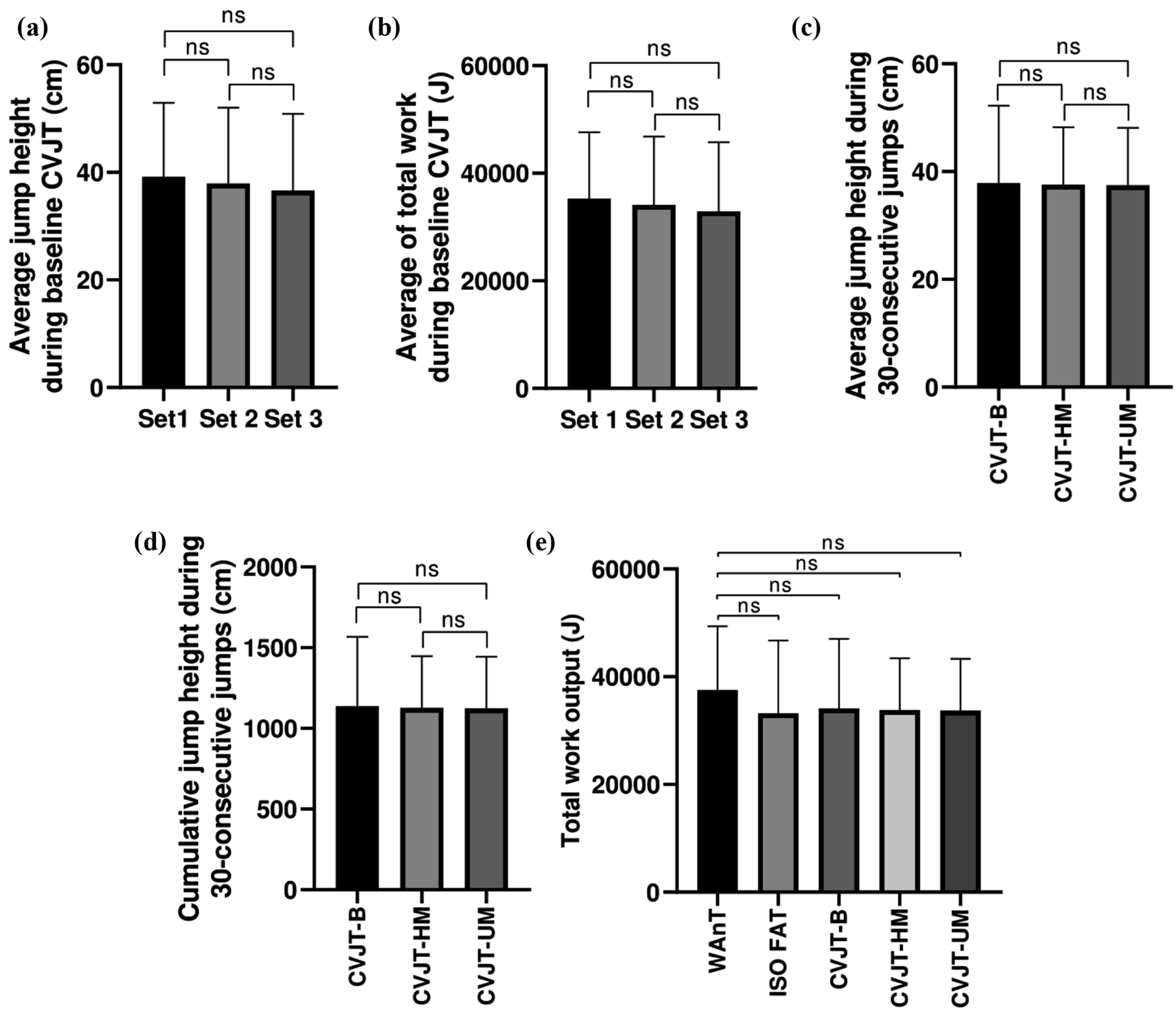

Fig. 2 Comparison of (**a**) average jump height of 3 sets of CVJT during baseline measures (CVJT-B), (**b**) average total work of 3 sets of CVJT during baseline measures, (**c**) average jump height during 30-consecutive jumps during baseline and following half-marathon and ultra-marathon races, (**d**) cumulative jump height during 30-consecutive jumps during baseline and following half-marathon and ultra-marathon races, (**e**) total work output among WAnT, ISO FAT, $CVJT_{\mathbf{baseline}}$, $CVJT_{\mathbf{half}}$, and $CVJT_{\mathbf{ultra}}$. **Note**: Data are presented as mean and standard deviation. ns: not significant; WAnT: Wingate anaerobic test, FAT: isokinetic fatigue test; CVJTb: continuous vertical jump test during baseline measures; CVJT-HM: continuous vertical jump test performed following half-marathon race; CVJT-UM: continuous vertical jump test performed following ultra-marathon race

measured during the WAnT (Fig. 3b, ICC: 0.883, SEM: 2637, MDC_{95}: 7302.34, $p < 0.0001$). TW measured during CVJT following the half marathon race was also positively significantly correlated with TW measured during the WAnT (Fig. 3c, ICC: 0.847, SEM: 2703, MDC_{95}: 7490.54, $p < 0.0001$). The measures of TW during CVJT following the ultra-marathon race were also positively correlated with TW measured during the WAnT (Fig. 3d, ICC: 0.842, SEM: 2735, MDC_{95}: 7553.70, $p < 0.0001$).

The results of the Pearson correlation coefficient analysis revealed that running speed during was inversely correlated with the total work output measured during CVJT-HM ($r = -0.477$, $p = 0.025$). Similarly, running speed during UM was found significantly correlated with CVJT-UM ($r = -0.595$, $p = 0.004$) performance. The results also showed that the increase in race time during HM races was inversely correlated with total work measured CVJT following HM race ($r = -0.457$, $p = 0.033$). The increase in race time during UM was also negatively correlated with total work measured during CVJT following UM race ($r = -0.568$, $p = 0.006$). However, there were no significant interactions between HR during HM and UM races and the measures of total work during CVJT-HM ($r = 0.351$, $p = 0.109$) and CVJT-UM ($r = 0.248$, $p = 0.265$), respectively.

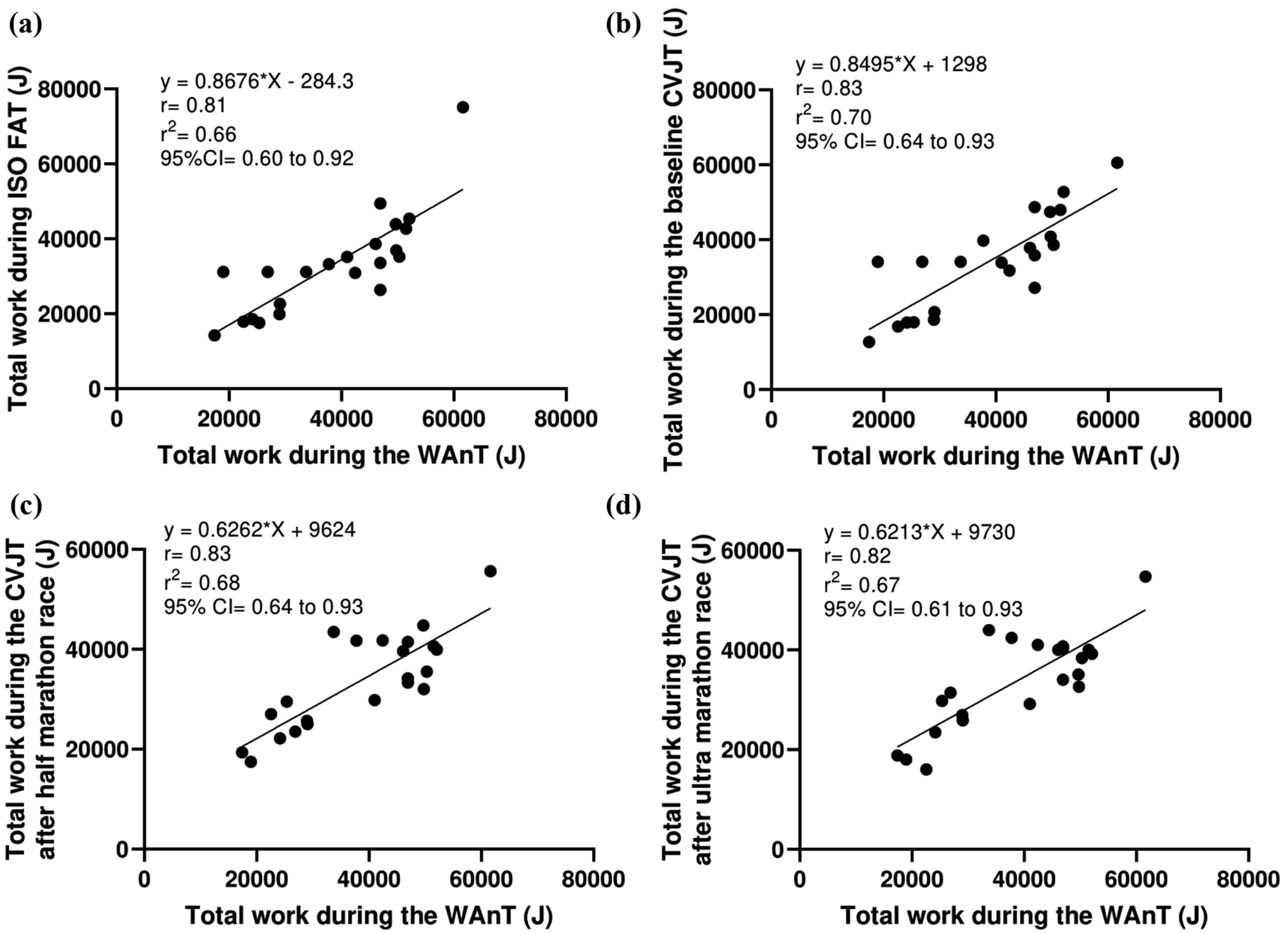

Fig. 3 The associations between the total work during (**a**) ISO FAT and WAnT, (**b**) baseline CVJT and WAnT, (**c**) CVJT after the half-marathon race and WAnT, (**d**) CVJT after the ultra-marathon race and WAnT

A Paired samples t-test was conducted to determine the effect of method selection on total work output. Paired comparisons showed that the total work output measured during the WAnT was not significantly greater than the total work output measured during the ISO FAT ($p = 0.769$), $CVJT_{baseline}$ ($p = 0.840$), $CVJT_{half}$ ($p = 0.702$), and $CVJT_{ultra}$ ($p = 0.622$), respectively. Bland-Altman analysis was used to determine absolute limits of agreement between predicted TW using the 30-consecutive vertical jump test components and TW measured during WAnT and ISO FAT while the Hedges g (g) assessed the difference's magnitude. The results of the Bland Altman limits of agreement analysis revealed medium effect sizes among the magnitude of the measures of TW ISO FAT ($p < 0.05$, g = 0.411), $CVJT_{baseline}$ ($p < 0.05$, g = 0.353), $CVJT_{half}$ ($p < 0.05$, g = 0.428), and $CVJT_{ultra}$ ($p < 0.05$, g = 0.435) compared to than those of TW WAnT, respectively. The 95% limits of the agreement of ISO FAT represented 23.46% of TW WAnT. The mean bias in total work between TW WAnT and ISO FAT was + 5398 ± 8035 with 95% limits of agreement of -10,351 to + 21,147 (Fig. 4a). Similarly, the 95% limits of agreement of $CVJT_{baseline}$ represented 32.81% of TW WAnT. The mean bias between TW WAnT and $CVJT_{baseline}$ was + 4515 ± 7366 with 95% limits of agreement of -9923 to + 18,952 (Fig. 4b). The CVJT measured did not reveal significant differences compared to baseline measures while the 95% limits of agreement of $CVJT_{half}$ and $CVJT_{ultra}$ represented 35.02% and 36.79% of TW WAnT, respectively. The mean bias between TW WAnT and $CVJT_{half}$ was + 4814 ± 7191 with 95% limits of agreement of -9281 to + 18,908 (Fig. 4c) while the mean bias between TW WAnT and $CVJT_{ultra}$ was + 4895 ± 7298 with 95% limits of agreement of -9409 to + 19,200 (Fig. 4d).

Discussion

The purpose of this study was to assess the validity of total work (TW) measured during the CVJT before and after HM and UM races compared to those of WAnT, ISO FAT. A secondary aim was to determine whether CVJT could be used interchangeably with TW measured during WAnT and ISO FAT for evaluating muscular fatigue resistance. The main findings were: (a) the number of sets had no significant effect on average jump height and total

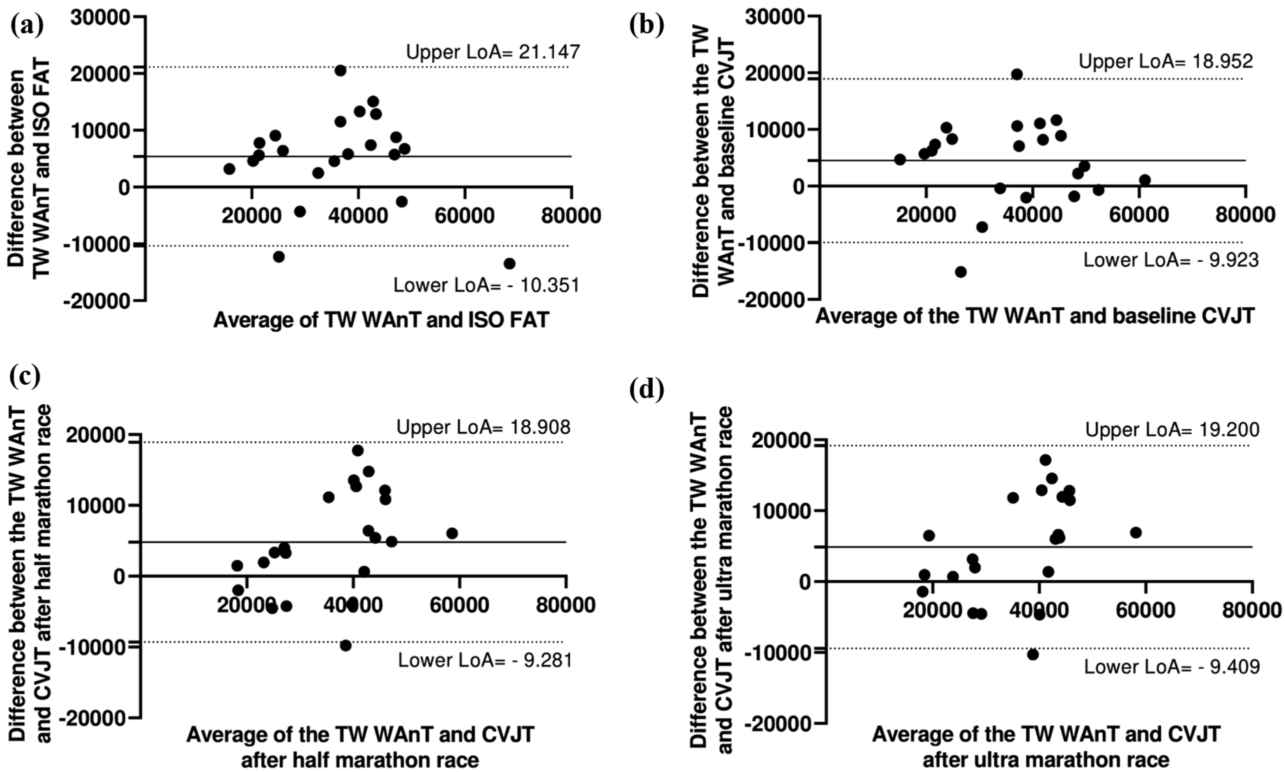

Fig. 4 Comparison of **(a)** total work (TW) measured during the Wingate anaerobic test with TW measured during the high-intensity isokinetic fatigue test (ISO FAT), **(b)** total work (TW) measured during the Wingate anaerobic test (WAnT) with TW measured during the baseline VJT, **(c)** total work (TW) measured during the Wingate anaerobic test (WAnT) with TW measured during the CVJT after half-marathon race, **(d)** total work (TW) measured during the Wingate anaerobic test (WAnT) with TW measured during the CVJT after ultra-marathon race

work output across the three test conditions at baseline; (b) HM and UM races did not significantly affect average or cumulative jump height; (c) TW output during WAnT and ISO FAT showed no significant difference compared to TW during the 30-consecutive vertical jump test at baseline, or post-HM and UM races; (d) TW from the WAnT was highly correlated with the measures of ISO FAT, CVJT-B, CVJT-HM, and CVJT-UM.

This study confirmed a strong relationship between TW during CVJT (before and after HM and UM races) and TW from WAnT and ISO FAT in a cohort of recreational distance runners. The ICC values are all above 0.80, which indicates a high level of reliability in the measurements for total work across different testing conditions (e.g., ICC for ISO FAT = 0.860, ICC for CVJT baseline = 0.883). These results indicate that the measurements of total work are highly consistent across the different testing conditions, meaning that these methods are reliable and can be used interchangeably with a high degree of confidence. While previous studies have shown similar relationships using jump height rather than TW, typically with untrained subjects, strength-trained non-cyclists, and strength-trained cyclists [25–27], no study has directly compared TW output from all three tests. The present study, therefore, provides experimental data supporting the use of WAnT, ISO FAT, and CVJT for interpreting muscular fatigue resistance.

The Pearson product-moment correlation analysis further supports the validity of TW derived from CVJT for assessing muscular fatigue resistance, consistent with previous research comparing peak or mean power during WAnT and peak or mean torque during isokinetic fatigue tests with moderately trained participants ($0.52 < r < 0.96$) [28]. Furthermore, in addition to significant correlations between TW from WAnT, ISO FAT, and CVJT, Bland-Altman analysis revealed moderate effect sizes among TW measurements from ISO FAT (g = 0.411), CVJT-B (g = 0.353), CVJT-HM (g = 0.428), and CVJT-UM (g = 0.435) compared to than those from WAnT, with the 95% limits of agreement (LOA) representing 23.46%, 32.81%, 35.02%, and 36.79% of TW from WAnT, respectively (Fig. 4a). These results do not align with previous research, which found the 95% LOA too large to justify interchangeability between WAnT and ISO FAT [29, 30].

In practice, this means that the interventions (WAnT vs. the other protocols) each show a noticeable, moderate difference, but none are overwhelmingly superior or different from the others based on this data. This suggests that based on the significant correlations in TW among WAnT, ISO FAT, and CVJT and the 95% LOA with moderate effect sizes, TW data derived from WAnT and ISO FAT may be directly translated into CVJT performance in the evaluation of muscular fatigue resistance in endurance runners. Also, to mitigate the impact of exercise mode on TW output, we combined the total work outputs from these tests into a single measure, considering total duration and repetitions. Combining isokinetic knee extension and flexion data for both limbs in ISO FAT and the sum of TW from a single set of 30 CVJT reps resulted in a smaller residual difference compared to WAnT while the level of agreement between the tests were optimal for making qualitative inferences about performance changes.

Currently, no single marker comprehensively captures optimal work output for maximizing training adaptation in endurance athletes. While total jump height is useful for monitoring chronic adaptations in endurance runners, the results should be interpreted with nuance to regulate training loads. Our results suggest that CVJT could serve as an alternative method for assessing muscular fatigue resistance when WAnT and ISO FAT are impractical, as CVJT is less time-consuming and easier to implement throughout a season. Also, our findings indicate that TW from CVJT may be used interchangeably with WAnT and ISO FAT in endurance athletes for monitoring muscular fatigue resistance in this population. Our results suggest that CVJT, WAnT, and ISO FAT can be considered valid methods for examining muscular fatigue resistance after strenuous activities like HM and UM in recreational distance runners, due to the strong relationships observed between the TW from these tests. The current study also highlights the sensitivity of CVJT-derived jump heights as an index of total work output under both non-fatigued and fatigued conditions in the evaluation of muscular fatigue resistance.

The effect sizes across all comparisons (ISO FAT, CVJT-B, CVJT-HM, and CVJT-UM) are similar, ranging between $g = 0.353$ and $g = 0.435$, which suggests that, while there is a difference between methods, the differences are moderate and might not be substantial in practical terms. This also suggests that all testing methods (ISO FAT, CVJT) can provide a similar estimate of total work compared to WAnT, but with some moderate variance. Also, the SEM values are relatively small, indicating that the measurement error for TW in the different tests is reasonable. However, the SEM still highlights that variability in individual test results due to measurement error exists and should be taken into account when interpreting data. In combination, these outcomes suggest that while the different methods for measuring total work (WAnT, ISO FAT, CVJT) are reliable and moderately different from each other, any small differences in total work would need to exceed certain thresholds to be considered true changes beyond measurement error.

Conclusions

This study provided evidence supporting the validity of the total work (TW) measured during the CVJT as a reliable method for assessing muscular fatigue resistance in endurance runners. The strong correlations between TW from CVJT, WAnT, and ISO FAT, both pre- and post-race, demonstrated that these tests could be used interchangeably for evaluating muscular fatigue resistance in endurance runners. Additionally, the data showed that while the interventions (WAnT vs. CVJT vs. ISO FAT) might influence results, the differences were moderate, indicating that none of the tests were overwhelmingly superior. These findings contribute to the understanding of how muscular fatigue resistance can be monitored and offer a viable alternative to more time-consuming and complex methods like WAnT and ISO FAT.

Nevertheless, interpreting the findings of the current study, it is important to note that the absence of significant changes could also suggest that other factors—like the recovery and training adaptations that runners may have developed—could offset the expected fatigue, especially in tests that aren't as specific to running or endurance activities. The jump test might not have captured the full extent of fatigue resulting from the running races, leading to a lack of significant differences post-race. Runners may have specific adaptations and fatigue patterns from long-distance running that might not translate directly to a vertical jump, which involves explosive power from a different set of muscles and movement mechanics. This could reflect the body's ability to adjust or compensate for fatigue in a familiar movement, or that the fatigue from the endurance events did not specifically impact the vertical jump as much as might have been expected.

Limitations

Despite significant findings, the current study also has several limitations. Although total jump height reflects mechanical work during the push-off phase and take-off velocity, it does not account for the time component of muscular force development. The WAnT, ISO FAT, and CVJT are valid but differ significantly in movement patterns (unilateral vs. bilateral, cyclic vs. acyclic) and test durations (several seconds vs. less than one second). Additionally, in the WAnT assessment, we used a manual crank for instantaneous loading and recording, which may have introduced a delay in reaching maximum resistance, potentially underestimating TW output. Moreover, the traditional method of calculating brake torque fails to consider rope-brake theory, and the rope tensions weren't measured to determine actual brake torque, leaving uncertainty about the accuracy of TW output reported by WAnT software. While we aimed to compare muscular fatigue resistance for short and long-distance events such as HM and UM, only recreational distance runners participated in the study. Furthermore, given that CVJT did not detect significant post-race changes, this lack of sensitivity to fatigue could limit its utility as a reliable measure for monitoring fatigue in endurance athletes. In this regard, CVJT might not be an effective tool for assessing cumulative fatigue or recovery status following long-duration, endurance-based events. Also, fatigue from long-duration events like HM or UM may not be easily captured by a jump-based test, which primarily focuses on explosive power and lower-body strength rather than the more specific forms of fatigue (e.g., endurance, cardiovascular, or neuromuscular fatigue) that might occur after a prolonged race. Consequently, the results of this test may not be indicative of the functional capacity or fatigue experienced by an athlete after running long races. Coaches and practitioners should be aware of its limitations and use it in combination with other tools that can measure endurance-specific fatigue (e.g., heart rate, lactate, pacing strategies, subjective assessments). This approach would provide a more accurate and comprehensive understanding of an athlete's fatigue and recovery status, ultimately enhancing the design and effectiveness of their training programs. Future research should investigate elite athletes in different race categories to determine if CVJT can offer similar results as WAnT and ISO FAT for assessing muscular fatigue resistance.

Practical implications

The results of this study suggest that the CVJT could be a useful and efficient tool for evaluating muscular fatigue resistance in endurance athletes, particularly when traditional tests like WAnT or ISO FAT are impractical. Given the moderate effect sizes and the ease of implementation, CVJT provides a feasible alternative for monitoring fatigue and performance changes throughout a season. This could be especially valuable in applied settings where time or resources are limited. Furthermore, as the CVJT has shown validity in capturing total work output even under fatigued conditions, it offers a reliable means of assessing how strenuous activities, such as half and ultra-marathons, impact performance. Coaches and sports scientists can incorporate CVJT into their training protocols to help track adaptations and regulate training loads more effectively for endurance athletes. Coaches can use these findings to predict and plan for fatigue management in longer endurance events. They can structure training programs to help athletes maintain better performance over extended periods or develop strategies to optimize energy usage during long races. Training to improve recovery time or ensure a more gradual pace may be beneficial for those targeting optimal race results over long distances. Also, coaches and practitioners can use these tests to monitor performance levels of athletes and track changes over time. Since the correlation between tests is strong (e.g., ISO FAT with WAnT, and CVJT with WAnT), practitioners can choose a test that fits the needs of their athletes, either for monitoring or assessment purposes, knowing that results will reflect endurance and fatigue-related abilities. Nevertheless, coaches may also need to complement CVJT with other fatigue monitoring methods (e.g., heart rate variability, perceived exertion scales, or lactate thresholds) to get a more comprehensive understanding of the recovery or fatigue state of their athletes.

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Author contributions
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Data availability
The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
The study was conducted according to the guidelines of the Declaration of Helsinki and approved by the ethics of Mersin University, Türkiye (Date of approval: 10/17/2022; Protocol number: 2022-043). All participants were informed about the purpose, content, and potential risks and benefits of the study, and signed an informed consent.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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