

Article

Influence of Isometric and Dynamic Fatiguing Protocols on Dynamic Strength Index

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Abstract: Background: Strength and conditioning experts widely recognize the dynamic strength index (DSI) as a tool for assessing an athlete's ability to utilize strength in dynamic actions. The DSI is calculated as the ratio of peak force in dynamic actions versus isometric ones. To date, the influence of fatigue on the DSI is still not fully understood. This study aimed to explore the effects of both dynamic and isometric fatigue tasks on the DSI. Methods: A total of 24 physically active participants underwent fatigue tests involving repeated countermovement jumps (dynamic) and repeated isometric mid-thigh pulls (isometric) in separate visits. Results: The results revealed a marked drop in performance, with dynamic force showing a more significant reduction ($p < 0.001$; $d = 1.57$) than isometric force ($p = 0.015$; $d = 0.30$). After the isometric fatigue task, the DSI increased, indicating a more substantial decline in isometric force ($p < 0.001$; $d = 1.75$) compared to dynamic force ($p = 0.313$; $d = 0.08$). Following this trend, the DSI decreased post-dynamic fatigue ($p < 0.001$; $d = 0.99$) and increased post-isometric fatigue ($p < 0.001$; $d = 3.11$). Conclusion: This research underscores the need to consider fatigue's task-specific effects on the DSI, enabling more tailored training methodologies for athletes.

Keywords: dynamic strength; vertical jump; mid-thigh pull; fatigue; task specificity



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1. Introduction

Strength and conditioning professionals utilize a diverse range of field and laboratory tests to evaluate the physical fitness and performance of athletes [1–3]. Recently, the dynamic strength index (DSI) has garnered significant attention [4–11], which is attributable to its simplicity and relatively well-established benchmarks for guiding training-related decisions. The DSI is defined as the ratio between peak force (PF) achieved during dynamic and isometric tasks [12] and is intended to represent the athlete's ability to utilize their force capacity during a dynamic task. Regarding lower limb assessment, most studies used a combination of the countermovement jump (CMJ) and the isometric mid-thigh pull (IMTP) to determine the DSI [8–10], although squat jumps [5,12] and isometric squats [4] have also been used. Given that the peak force in CMJ is typically lower than in IMTP, the DSI values are commonly lower than 1.0. A DSI below 0.60 suggests a need for athletes to prioritize ballistic or plyometric training to optimize their force application in dynamic tasks [12]. Conversely, a DSI exceeding 0.80 implies that athletes, already proficient in using most of their force capacity in dynamic tasks, should emphasize maximal strength training to enhance maximal force production capability [12]. The DSI has been shown to be highly reliable [5,7,8,10] and to decrease as a consequence of maximal strength training [8].

To the best of our knowledge, no study has investigated the influence of fatigue on the DSI. The changes in isometric and dynamic force production under the influence of fatigue are not necessarily uniform. Diverging responses in these capacities have been noted after specific fatiguing tasks like cycling at varying intensities [13]. In addition, after a running event, lower limb isometric force and maximal jump power decreased by ~25–30% and ~14%, respectively, with only a moderate correlation between the two [14]. Similarly, a significant decrease in knee extension and plantar flexion maximal force (22% and 17%, respectively) was observed after a marathon run, with no change in CMJ force [15]. In addition, throughout a 12-week strength training program with deliberate overarch, no relationship was found between changes in CMJ performance and changes in maximal voluntary force [16]. More specific to the DSI evaluation, another recent study reported larger decrements in both CMJ height and IMTP force after heavy resistance training compared to isometric training [17]. Furthermore, it has been suggested that the jumping strategy can be altered to maintain the same performance despite losses in maximal voluntary force [18]. If fatigue differently affects isometric and dynamic force capacities, it could distort the DSI values. Assessing the DSI under fatigue conditions might yield insights distinct from the measurements at rest. It is conceivable, though still speculative, that athletes showing the most pronounced DSI decrease under fatigue (indicating a more substantial drop in dynamic compared to isometric force) might benefit from enhancing their dynamic strength endurance.

Given the absence of research on fatigue's impact on the DSI, our study was conceived as a proof-of-concept to examine whether the DSI decreases after fatiguing dynamic contractions. To further investigate whether these changes depend on the fatigue task, we also examined the DSI following an isometric fatigue task. Our primary objective was to ascertain the effects of dynamic (repeated CMJ) and isometric (repeated IMTP) fatigue tasks on the DSI, that the repeated CMJ task would disproportionately reduce force-production in CMJ compared to IMTP, leading to a lowered DSI. An opposite effect (increased DSI) was expected following repeated IMTPs, which would show that changes in the DSI depend on the type of fatiguing task. The findings of our study will have significant implications for physical fitness assessments in sports environments. Specifically, the necessity for coaches and strength and conditioning professionals to carefully consider the sequencing of tests within a session, will be highlighted. If different fatiguing tasks differentially affect dynamic and isometric force capacities, performing other tests prior to assessing the DSI could lead to distorted DSI values. This distortion arises because fatigue from earlier tests, whether dynamic or isometric in nature, may not uniformly impact an athlete's force production capabilities. Consequently, when an assessment session includes various tests, the order in which they are conducted could influence the outcomes.

2. Materials and Methods

2.1. Participants

We used G*Power 3.1 software (Heinrich Heine University, Düsseldorf, Germany) for calculating sample size for a within-factors analysis of variance (ANOVA) (effect size (f) = 0.25; α error = 0.05, and power = 0.90). At least a medium effect of fatigue could be expected based on previous studies; therefore, a partial η^2 was set at 0.06 and transformed into the f -effect size metric within the software. The sample size calculation indicated that at least 20 participants were needed for the study. Therefore, 24 physically active volunteers participated in this study (Table 1). The participants were kinesiology, physical therapy and physical education students, reported to engage in 4.1 ± 2.1 exercise sessions per week (range: 2–8), and specifically 1.9 ± 1.8 resistance exercise sessions (range: 1–5) in the past year. An additional inclusion criterion for the study was regular physical activity at least twice a week in the last 5 years. The exclusion criteria were knee injuries, chronic diseases, history of lower back pain or acute injuries in past 2 years. The study was approved by the Slovenian Medical Ethics Committee (approval no. 0120-99/2018/5) and was conducted according to the Declaration of Helsinki. Participants were informed about the testing

procedures before they signed an informed consent form. They were instructed to avoid any strenuous exercise at least two days prior to the testing sessions. The measurements were taken in a laboratory setting on two occasions with one week of rest in between.

Table 1. Basic participant information.

	N	Age (Years)	Body Height (cm)	Body Mass (kg)
Female	12	23.4 ± 1.9	163.9 ± 6.1	58.2 ± 5.4
Male	12	25.9 ± 3.5	181.0 ± 5.1	77.2 ± 7.0
All	24	24.7 ± 3.0	172.4 ± 10.3	67.7 ± 11.5

N—number of participants.

2.2. Study Design and Procedures

A repeated measure cross-over study design was used to explore the effects of two different fatiguing protocols (repeated CMJ and repeated IMTP) on DSI. Two separate visits for each fatiguing protocol were carried out at the same time of the day, at least 10 days apart. The order of the conditions (CMJ and IMTP protocols) between visits was randomized for each participant. The measurements were performed in a laboratory setting using a portable bilateral force platform (type 9260AA, Kistler Instrumente, AG, Winterthur, Switzerland). Participants performed a general 10 min warm-up consisting of 6 min of alternating step-ups on a 25 cm high bench (80 beats per min) following arm, hip, knee and ankle mobility exercises (10 reps each), dynamic stretches of hip flexors, knee extensors and flexors (10 reps each) and bodyweight resistance exercises (heel raises, squats and crunches; 10 repetitions each). After the general warm-up, each subject performed 5 submaximal CMJs and IMTPs at 70, 80 and 90% of self-estimated maximal effort with 30 s of rest between each repetition, to familiarize themselves with the tasks. Before and after each fatiguing protocol, participants performed three bilateral CMJs with 30 s of rest between successive jumps and three maximal IMTPs with 30 s rest between repetitions to determine participants' maximal CMJ jump height and maximal produced force during IMTP. The order of the two tests was also randomized for each participant (the same order was followed by individual participants before and after the fatigue protocols). The recovery period between the fatigue protocols and subsequent testing was minimized, with ~20 s elapsing between the cessation of the fatigue protocols and first repetition of subsequent testing. The total duration of CMJ and IMTP testing was ~180–220 s, while the duration of the fatigue protocols was not pre-determined; rather, it was based on performance decline (see below).

2.3. Countermovement Jumps

Participants began the exercise execution in a standing, comfortable bilateral stance with both legs fully extended and feet in the hip-width position over the center of two parallel force platforms, while their hands were placed on the hips during the whole execution of the jump. To maximize CMJ performance, the participants were instructed to jump as high and as fast as possible [19] with extended legs after performing a countermovement to a self-selected depth [20,21]. Three repetitions with a 30 s rest between them were performed.

2.4. Isometric Mid-Thigh Pulls

During the IMTP execution, the body position was very similar to the second pull of the clean and the clean grip IMTP exercise: upright torso, slight flexion in the knee resulting in the some dorsiflexion, shoulder girdle retracted and depressed, shoulders above or slightly behind the vertical plane of the bar, feet roughly centered under the bar approximately hip width apart, knees underneath and in front of the bar, and thigh in contact with the bar [22]. For each participant, we determined the starting position of the IMTP before the warm-up. The position was self-preferred knee (within the range: 125–145°) and hip (within the range: 140–150°) angle. The same position was used in

all repetitions using hip and knee angle and position of the bar (height) on the thighs. Participants were provided with lifting straps and were instructed to pull on the bar as hard as possible. Three repetitions with a 30 s rest between them were performed.

2.5. Fatiguing Protocols

The repeated CMJ fatiguing protocol involved performing repetitive bilateral CMJs separated by 2 s of break until a 20% reduction in maximal CMJ height was observed for three consecutive repetitions. The IMTP fatiguing protocol consisted of performing repetitive maximal IMTPs until the peak force dropped for 40% for three consecutive trials compared to the best trial. The software (MARS, 2875A, Kistler) tracked the repetitions in real-time and automatically stopped the protocol once the specified thresholds were reached. The decrement threshold was determined in a pilot study so that both fatiguing protocols caused similar rates of perceived exertion (RPE). Participants were asked to report their RPE before and after each fatigue protocol on a 1–10 scale, with 1 representing “hardly any exertion”, and 10 representing “maximal effort, which is impossible to maintain for more than a very short time”.

2.6. Data Acquisition and Analysis

All CMJs and IMTPs were performed on two parallel force platforms fixed in an iron frame (Kistler, model 9260AA6, Winthertur, Switzerland). The vertical ground force from each force platform were synchronously acquired at 1000 Hz via Kistler’s MARS (Measurement, Analysis and Reporting Software) and low pass filtered with a moving average with a 5 ms time window. CMJ peak force (PF) was taken from the force–time trace to enable the DSI calculation. The jump height was calculated by the software based on take-off velocity, as calculated from the force impulse. The onset of the jump was determined as the instance when the signal dropped below 5 standard deviations of the subject weight, minus 30 ms. This approach has been shown to maximize the reliability of the jumps, compared to other thresholds such as 1% of subjects weight or 10 N [23]. In IMTP test, the peak force was taken as the largest mean force in 1 s intervals. Similar to CMJ, the threshold of 5 standard deviations of subject’s weight was used to determine the onset of IMTP in accordance to the recommendations [24]. Subsequently, DSI variables were calculated from PF obtained in CMJ and IMTP as follows:

$$DSI(\%) = \frac{\text{Peak force in CMJ}}{\text{Peak force in IMTP}}$$

2.7. Statistical Analysis

For all outcome variables in CMJ and IMTP, the average of the three repetitions was used for statistical analysis. To check the robustness of the results, the analysis was also run with the best repetitions. This had a small effect on descriptive statistics, while the effect sizes and *p*-values were very similar. The data are presented as means $\pm$ standard deviations. The normality of the data distributions for all variables was verified with Shapiro–Wilk test (all $p \geq 0.085$). Intra-class correlation coefficients (ICC; single measures, absolute agreement) and typical errors (TE) expressed as percentage of the mean were calculated to assess reliability, considering pre-fatigue values of both sessions. We also included 95% confidence intervals (CI) for both ICC and TE. An ICC value lower than 0.50 was considered as indicative of poor reliability, values between 0.50 and 0.75 as moderate reliability, values between 0.75 and 0.90 as good reliability, and values greater than 0.90 as excellent reliability [25]. In addition, reliability was considered as acceptable when TE was $<10\%$ [26]. Systematic bias was also assessed using paired-sample *t*-tests. Two-way repeated-measure analysis of variance (ANOVA) was used to determine the influence of time (pre-/post-fatigue) and fatigue protocol (CMJ, IMTP) on CMJ height, CMJ PF, IMTP PF, and DSI. For statistically significant effects of ANOVAs and *t*-tests, partial η^2 and Cohen’s *d* were also calculated as measures of effect size. The η^2 values were considered to indicate no effect (<0.01), small effect (0.01–0.039), a medium effect (0.06–0.14) and a large effect

(>0.14), whereas the effect sizes according to Cohen's d were considered as trivial (<0.20), small (0.20–0.50), medium (0.50–0.80) and large (>0.80) [27]. The threshold for statistical significance was set at $\alpha < 0.05$ and all analyses were carried out in SPSS statistical software (version 25.0, IBM, New York, NY, USA).

3. Results

3.1. Reliability and Pre-Fatigue Outcomes

The relative reliability was excellent for CMJ height, CMJ PF and IMTP PF (ICC = 0.96–0.97; lower bound for 95% CI = 0.90–0.91). The DSI showed good reliability (ICC = 0.87), with 95% CI spanning from moderate to excellent reliability (0.72–0.94). All variables showed acceptable absolute reliability (TE = 4.2–5.7%; upper bound of the 95% CI = 5.9–8.0%).

Pre-fatigue CMJ height was statistically significantly lower during the IMTP fatigue session (33.7 ± 6.8 cm) than during the CMJ fatigue session (35.0 ± 7.3 cm) ($p = 0.009$), but the effect was trivial ($d = 0.18$). No differences between sessions were noted for CMJ PF, IMTP PF and the DSI ($p = 0.507$ – 0.876).

3.2. The Effects of Fatigue on RPE, CMJ, IMTP and DSI

The mean number of repetitions performed in the IMTP task was 64.5 ± 41.1 (minimum = 18; maximum = 162). In the case of CMJ, the mean number of repetitions was 36.7 ± 15.1 (minimum = 20; maximum = 92).

The participants evaluated their RPE as 1.1 ± 0.4 pre- and 7.6 ± 0.9 post-CMJ-fatigue protocol (difference 6.5 ± 0.9). Before the IMTP-fatigue protocol, the participants reported the RPE at 1.0 ± 0.0 while the post values were 7.9 ± 1.03 (difference: 6.9 ± 1.0). Wilcoxon signed rank test showed no significant differences between pre/post changes in RPE between the CMJ- and IMTP-fatigue protocols ($z = -1.61$, $p = 0.11$).

The descriptive statistics for CMJ height, CMJ PF, IMTP PF and the DSI are shown in Table 2. For all variables, there were large effects from time ($p < 0.001$; $\eta^2 = 0.82$ – 0.94), exercise ($p < 0.001$; $\eta^2 = 0.53$ – 0.91), as well as the interaction between time and exercise ($p < 0.001$; $\eta^2 = 0.47$ – 0.93).

Table 2. The descriptive statistics.

		CMJ Fatigue	IMTP Fatigue	ANOVA			
					Time	Fatigue	Interaction
CMJ height (cm)	Pre-fatigue	35.0 ± 7.3	33.7 ± 6.8	p	0.001	0.001	0.001
	Post-fatigue	23.9 ± 5.4	31.7 ± 6.1	η^2	0.87	0.67	0.87
CMJ peak force (N)	Pre-fatigue	1726 ± 369	1715 ± 341	p	0.001	0.001	0.001
	Post-fatigue	1490 ± 343	1661 ± 311	η^2	0.8	0.53	0.47
IMTP peak force (N)	Pre-fatigue	2262 ± 673	2256 ± 667	p	0.001	0.001	0.001
	Post-fatigue	2234 ± 647	1326 ± 402	η^2	0.89	0.86	0.89
DSI (a.u.)	Pre-fatigue	0.79 ± 0.12	0.79 ± 0.12	p	0.001	0.001	0.001
	Post-fatigue	0.68 ± 0.09	1.30 ± 0.21	η^2	0.94	0.91	0.94

CMJ—countermovement jump; IMTP—iso-metric mid-thigh pull; DSI—dynamic strength index.

A closer inspection of the pairwise differences revealed that the decrements in performance were more pronounced when the assessment task matched the fatiguing task. For instance, CMJ height was largely decreased after CMJ fatigue ($p < 0.001$; $d = 1.57$), but only showed a small decrease by IMTP fatigue ($p = 0.015$; $d = 0.30$). Similarly, CMJ PF was moderately reduced after CMJ fatigue ($p < 0.001$; $d = 0.67$), but was again only trivially affected by IMTP fatigue ($p = 0.007$; $d = 0.17$). In contrast, IMTP PF was largely reduced after IMTP fatigue ($p < 0.001$; $d = 1.75$), but was not affected by CMJ fatigue ($p = 0.313$; $d = 0.08$). As expected from the analysis of its constituent variables, the DSI was largely reduced after CMJ fatigue ($p < 0.001$; $d = 0.99$) and largely increased after IMTP fatigue ($p < 0.001$; $d = 3.11$).

4. Discussion

This study was conducted to examine the influence of dynamic (repeated CMJ) and isometric (repeated IMTP) fatigue tasks on the DSI. As we hypothesized, the fatigue induced by repeated CMJ reduced PF to a greater extent in CMJ than in IMTP, which resulted in a greatly decreased DSI. This suggests that caution should be taken when interpreting DSI values under the influence of fatigue. We also observed an opposite effect (increased DSI) after repeated IMTP, demonstrating that fatigue effects are highly task-specific. To the best of our knowledge, this is the first study that assessed the effects of fatigue on the DSI. Future research should consider investigating the practical relevance of the DSI in the fatigued state. The findings of this study suggest that coaches should either (a) conduct DSI assessments at the outset of testing sessions or (b) allow sufficient recovery between tests to ensure accurate evaluation of an athlete's dynamic strength capabilities.

Previous research has documented that the magnitude of fatigue is specific both to the fatiguing protocol and measurement tasks [13–15,28,29]. Therefore, our results were expected. Several underlying mechanisms could explain why notable decreases in performance were observed only when the measurement task corresponded to the fatiguing task. Although the main agonist muscles for both tasks were the same, the differing muscle activations between CMJ and IMTP could underlie our observations. For instance, vastus medialis was reported to exhibit ~83.5% maximal voluntary activity during IMTP [30], while the values can be much higher (~150–190%) in CMJ [31]. In addition, CMJ involves an eccentric and a concentric contraction, and stretch-shortening cycle, and is partially underpinned by different mechanisms than isometric force production (e.g., musculotendinous stiffness [32] and rate of force development [33]). Given the importance of the rate of force development in CMJ, it could be hypothesized that motor unit firing rate, speed of motor neuron recruitment and excitation–contraction coupling are the main limiting mechanisms in this task [34,35], while reductions in isometric force are largely explained by peak muscle activation [36]. While the exact mechanisms cannot be elucidated from our experiment, it is clear that CMJ and IMTP both highly induce task-specific fatigue effects, which are also reflected in the DSI.

Specific differences in motor unit recruitment and motor commands between isometric and dynamic movements can provide further insight into the observed results in the dynamic strength index (DSI). Isometric muscle contractions, such as in the IMTP, require continuous motor unit recruitment and put a higher demand on the central nervous system. This demand can lead to central fatigue, involving neurotransmitter depletion, decreased excitability of motor neurons, and reduced voluntary drive to the muscles. Additionally, isometric contractions predominantly recruit both slow-twitch and fast-twitch muscle fibers, which contribute to decreased peak force output during IMTP and consequently higher DSI values after IMTP fatigue [37]. On the other hand, dynamic movements like the countermovement jump (CMJ) involve a broader range of motion and external movement, which can lead to more peripheral fatigue. During CMJ, eccentric contractions place high mechanical stress on muscle fibers, and repeated CMJs can cause the accumulation of metabolic waste products to a greater extent [38]. Performing repeated CMJs preferentially recruits fast motor units, especially during eccentric contractions. Furthermore, the concentric push-off phase in CMJ is predominantly affected by metabolic fatigue [38]. Consequently, the short-term performance depression due to the accumulation of lactate and other metabolic markers results in a greater impairment of explosive performance and a decrease in the DSI after repeated CMJ. Overall, the interplay of different fatigue mechanisms, such as central fatigue during IMTP and peripheral and metabolic fatigue during CMJ, can explain the task-specific effects on the DSI observed in this study. These distinct fatigue responses between isometric and dynamic movements underscore the importance of considering the specific demands of each task when assessing an athlete's strength capacity and interpreting DSI values. Understanding these fatigue-related nuances in motor unit recruitment and energy systems can aid in designing more effective and targeted training strategies to optimize athletic performance based on DSI assessments.

The notable differences in the DSI values observed after IMTP fatigue (from 0.79 ± 0.12 to 1.30 ± 0.21) compared to CMJ fatigue (from 0.79 ± 0.12 to 0.68 ± 0.09) were not attributed to differences in perceived exertion (RPE) during the two fatigue protocols. Previous studies have demonstrated that human motor control systems can adapt the coordination of lower limbs to maintain task performance despite fatigue, and dynamic movements like CMJ can also affect other factors such as muscle stiffness [39,40]. In contrast, during isometric contractions, both the muscles and the central nervous system are more heavily affected by fatigue. The findings also suggest that IMTP fatigue predominantly affected slow muscle fibers, while the fast-twitch fibers, responsible for generating peak force during CMJ, were only slightly affected after IMTP fatigue. Additionally, the longer isometric contractions in the IMTP-fatigue protocol likely led to greater metabolic fatigue due to greater blood flow obstruction [41], resulting in a higher accumulation of metabolites compared to the dynamic CMJ-fatigue protocol. This greater metabolic fatigue could contribute to the larger change in the DSI observed after the IMTP-fatigue task. Another crucial difference is the presence of eccentric muscle actions during dynamic contractions (such as CMJ), which are associated with higher force production capabilities compared to isometric actions. As the IMTP lacks an eccentric component, the peak force during CMJ (eccentric force) was not significantly affected by IMTP fatigue. In contrast, the peak force during IMTP was substantially impacted, leading to a greater change in the DSI after IMTP fatigue.

Limitations

Several limitations of the present study need to be addressed. The notable variations in the DSI changes after the two fatigue protocols may be attributed to multiple factors, including differences in muscle fiber recruitment, metabolic fatigue, the presence of eccentric muscle actions, and the specific demands of each task. However, our study was not designed to elucidate the exact mechanisms underlining the decreases in IMTP and CMJ performance. There is a need to consider the unique effects of different fatigue protocols on DSI assessments to accurately interpret an athlete's strength capacity during dynamic and isometric tasks. Understanding these underlying mechanisms could aid in the development of targeted training strategies to optimize performance in specific athletic contexts. The depth of the countermovement was not controlled across the experiment (both measurement and fatigue trials). While the performance in CMJ is maximized when the participants are instructed to jump "as fast and as high as possible" and using self-selected depth [19,21], the relationship between power output and CMJ performance is notably affected by countermovement depth [42]. Therefore, the effects of fatigue reflected in decreased power and force output may not reflect the changes in performance. Finally, the fatigue tasks were matched based on a drop in performance (PF in IMTP, height in CMJ), but not on the muscle workload or number of repetitions. Therefore, it is important to emphasize again that the results of the present study are meant to be seen only as proof of concept—showing the potential for fatigue to influence DSI values, which warrants caution for its practical application. Studies examining the underlying mechanisms of the differences between dynamic and isometric fatiguing tasks should be designed differently.

5. Conclusions

Our study highlights the importance of considering the specific demands of fatigue protocols when interpreting DSI values. The fatigue-induced changes in the DSI are task-specific, with dynamic fatigue affecting CMJ performance more than IMTP and vice versa. These differences are attributed to various factors, including muscle fiber recruitment, metabolic fatigue, and the presence of eccentric muscle actions. Understanding these nuances may aid in designing targeted training strategies to optimize athletic performance based on DSI assessments. Further research is warranted to explore the practical relevance of the DSI in fatigued states and its implications for training interventions.

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Informed Consent Statement: Participants were informed about the testing procedures before they signed an informed consent form. Informed consent was obtained from all subjects involved in the study.

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