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Recreational runners who recovered from COVID-19 show different running kinetics and muscle activities compared with healthy controls

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ABSTRACT

Background: Social isolation through quarantine represents an effective means to prevent COVID-19 infection. A negative side-effect of quarantine is low physical activity.
Research question: What are the differences of running kinetics and muscle activities of recreational runners with a history of COVID-19 versus healthy controls?
Methods: Forty men and women aged 20–30 years participated in this study and were divided into two experimental groups. Group 1 (age: 24.1 ± 2.9) consisted of participants with a history of COVID-19 (COVID group) and group 2 (age: 24.2 ± 2.7) of healthy age and sex-matched controls (controls). Both groups were tested for their running kinetics using a force plate and electromyographic activities (i.e., tibialis anterior [TA], gastrocnemius medialis [Gas-M], biceps femoris [BF], semitendinosus [ST], vastus lateralis [VL], vastus medialis [VM], rectus femoris [RF], gluteus medius [Glut-M]).
Results: Results demonstrated higher peak vertical ($p = 0.029$; $d=0.788$) and medial ($p = 0.004$; $d=1.119$) ground reaction forces (GRFs) during push-off in COVID individuals compared with controls. Moreover, higher peak lateral GRFs were found during heel contact ($p = 0.001$; $d=1.536$) in the COVID group. COVID-19 individuals showed a shorter time-to-reach the peak vertical ($p = 0.001$; $d=3.779$) and posterior GRFs ($p = 0.005$; $d=1.099$) during heel contact. Moreover, the COVID group showed higher Gas-M ($p = 0.007$; $d=1.109$) and lower VM activity ($p = 0.026$; $d=0.811$) at heel contact.
Significance: Different running kinetics and muscle activities were found in COVID-19 individuals versus healthy controls. Therefore, practitioners and therapists are advised to implement balance and/or strength training to improve lower limbs alignment and mediolateral control during dynamic movements in runners who recovered from COVID-19.

1. Introduction

In March 2020, the World Health Organization (WHO) declared the COVID-19 outbreak as a pandemic. In October 2020, WHO reported ≥ 42 000 000 confirmed cases globally, resulting in approximately 1 150 000 deaths [1]. Over 100 countries enforced social distancing as a means to reduce the rate of COVID-19 transmission [2]. However, social isolation such as quarantine has a negative effect on individuals' physical activity [3]. In fact, there is evidence of increased sedentarism during the pandemic illustrated in enhanced media use such as time watching TV (72.3%), usage of social media (81.9%) and electronic gadgets (82.7%) [4,5]. With increased media exposure, a concomitant reduction was found in time spent performing aerobic exercise (e.g., walking and jogging) in the range of 40–60% was noted for [4,5].

Individuals who are COVID-19 infected often show a plethora of symptoms in the cardiorespiratory [6] and the central nervous system [7]. For instance, COVID-19 individuals compared with healthy controls had lower maximal oxygen uptake [6] and signs of polyneuropathy and myopathy [8]. In addition, social distancing and /or quarantine result in reduced levels of physical activity which again induce losses in muscle mass, strength, and power [9,10]. For example, Tuzun et al., [10] demonstrated lower muscle strength and greater fatigue symptoms in

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individuals suffering severely from COVID-19 compared with controls. During dynamic contractions, previous research supports the theory that the muscle activity indicates the state of activation of the contractile element, which is quite different from the tension generated by the muscle [11]. Different neuromuscular symptoms (e.g., muscle weakness) and diseases (e.g., encephalopathy and cranial neuropathy) have previously been reported for patients who suffered from COVID-19 [12]. Taken together, these COVID-19 related symptoms together with low physical activity levels may affect running kinetics and muscle activities in individuals who recovered from COVID-19.

It has previously been shown that peak vertical impact ground reaction forces (GRFs) and vertical loading rates are predictors of running-related injuries [13]. More specifically, there is evidence that greater loading rates are related to a shorter time to peak impact vertical GRFs, which could increase the risk of sustaining injuries [14]. Recent studies reported that free moments of the foot can be used as an index of torsional stress of the lower limbs [15]. Free moments describe the vertical moment applied in the center of pressure. Of note, Holden and Cavanagh [15] have shown that free moments are associated with tibial stress fractures in distance runners. These biomechanical variables are important to define the etiology of running-related injuries and should be explored to better understand the potential benefits of injury preventive exercise protocols (e.g., strength and/or balance training). To the best of our knowledge, there is no study available that examined GRFs and muscle activities during running in patients with a history of COVID-19 versus healthy controls. Therefore, the aim this study was to compare running kinetics and muscle activities of recreational runners with a history of COVID-19 compared with healthy controls. With reference to the relevant literature [9,10,16,17], we hypothesized that GRFs during running are different in individuals with a history of COVID-19 compared with their healthy peers. In addition, we expected different muscle (e.g., vastus medialis) activity in COVID-19 individuals compared with their healthy peers [16,17].

2. Methods

2.1. Study design and participants

We used the freeware tool G*Power to calculate a one-sided a priori power analysis [18]. The included program variables were an assumed Type I error of 0.05, a Type II error rate of 0.20 (80% statistical power), and an effect size of 0.85 for the second peak of vertical ground reaction force based on the outcomes of a similar study [19]. The analysis revealed that at least 18 participants per group would be needed to find large-sized between group differences for measures of running mechanics. To prevent falling below the critical number of subjects due to test related injuries, 40 men and women aged 20–30 years were enrolled in this study (Table 1). A confirmed case of COVID-19 was defined as a positive result on real-time reverse-transcription polymerase chain reaction analysis of throat swab specimens and/or radiologic assessments including chest computer tomography according to the classification of the Radiological Society of North America [20]. The degree of COVID-19 severity (severe vs non-severe) at the time of hospitalization was defined by using the American Thoracic Society Guidelines for community-acquired pneumonia [21]. Participants with a history of COVID-19 were included in the COVID-19 group. All participating COVID-19 individuals were categorized as patients with severe symptoms who were hospitalized between 19 and 23 days. Running mechanics of COVID-19 individuals were always tested two weeks after hospitalization. Before COVID-19 treatment in hospital, participants ran ~ 17 km/week on average. Healthy age and sex-matched controls were used as comparator. Individuals from the control group ran on average ~ 17 km/week. All participants were heel strikers. Foot strike was monitored through subjective observation of the examiner and objective kinetic data provided from the force plate [22]. Individuals were included in the study if they had recovered from COVID-19. Participants were excluded from the study after clinical examination if they showed signs of hypertension, diabetes, thyroid disease, cardiovascular and cerebrovascular disease, malignancy, and chronic kidney disease and rheumatologic diseases. Written informed consent was provided from all patients prior to the start of the study. The study was conducted in accordance with the latest version of the Declaration of Helsinki. Ethical approval was obtained from the local ethical committee.

Table 1
Participant characteristics according to group allocation. P-values indicate between group differences in the respective parameters. NA stands for not applicable.

Characteristics		Healthy controls	COVID-19	p-value
Parameters	Sex (male, female)	(10, 10)	(10, 10)	NA
	Age (years)	22.2 ± 1.9	24.1 ± 2.95	0.955
	Height (cm)	177.9 ± 5.4	178.0 ± 6.2	0.861
	Body mass (kg)	75.6 ± 7.8	75.0 ± 8.2	0.615
	Running experience (km/week)	16.9 ± 1.9	17.0 ± 2.1	0.744

2.2. Assessment of running kinetics

A force plate (Bertec Corporation, Columbus, OH, United States) was used to record GRF data during running at a sampling rate of 1000 Hz. Participants were asked to run at a constant speed of ~ 3.3 m/s over a 20 m walkway. Two sets of infrared photocells positioned 6 m apart along the length of the runway were used to monitor running speed and to set the speed at a velocity of 3.3 m/s ± 5% [23]. The photocells were placed at shoulder level to prevent an onset due to arm swing [24]. Running at this speed has previously been used for determining running-related injury risk factors [25]. Three practice trials were performed to familiarize the participants with the test before performing five test trials with a 5-min rest between each trial to minimize the effects of fatigue. Kinetic data were processed as described earlier by Jafarnezhadgero et al. [26]. GRFs were low pass filtered at 20 Hz (4th order Butterworth filter, zero lag). Specific running characteristics (heel strike and toe-off) were identified using the Bertec force plate. For this purpose, a 10 N threshold was used to detect the stance phase of the running cycle. The following dependent variables were extracted from GRF data [26]: First (FZ_{HC}) and second vertical peak force (FZ_{PO}). Braking (FY_{HC}) and propulsion forces (FY_{PO}) were recorded from the anterior–posterior force curve. From the medial-lateral curve, we calculated the positive (lateral) peak (FX_{HC}) which occurs right after heel contact. Moreover, we additionally assessed the negative peak which corresponds to the transfer of body mass to the contralateral limb (FX_{PO}). GRF amplitudes were normalized to body weight (BW) and reported in %BW. The free moment (FM) of the foot was also computed. Moreover, FM amplitudes were normalized with regards to BW × height. All running variables were averaged across five trials [26]. For stance phase analysis, GRF data were normalized to 101 data points.

2.3. Assessment of muscle activities

A wireless electromyographic (EMG) system (EMG Pre-Amplifier, Biometrics Ltd., Nine Mile Point Ind. Est., Newport, United Kingdom) with eight pairs of bipolar Ag/AgCl surface electrodes (25 mm center-to-center distance; input impedance of 100 MO; and common-mode rejection ratio of>110 dB) was used to record muscle activity of the tibialis anterior (TA), gastrocnemius medialis (Gas-M), biceps femoris (BF), semitendinosus (ST), vastus lateralis (VL), vastus medialis (VM), rectus femoris (RF), and gluteus medius (Glut-M) of the right leg [27]. These muscles were selected due to their stabilizing and propulsion function during walking and running [28,29]. A die-cut medical-grade double-sided adhesive tape (T350, Biometrics Ltd., Nine Mile Point Ind. Est., Newport, United Kingdom) was used to attach the electrodes to the muscle bellies. For the TA muscle, the electrodes were placed at 1/3 on the line between the tip of the fibula and the tip of the medial malleolus. For the Gas-M muscle, the electrodes were placed on the most prominent part of the muscle belly. For the VM muscle, the electrodes were placed at 80% on the line between the anterior spina iliaca superior and the joint space in front of the anterior border of the medial ligament. For the VL muscle, the electrodes were placed at 2/3 on the line from the anterior spina iliaca superior to the lateral side of the patella. For the RF muscle, the electrodes were placed at 50% on the line from the anterior spina iliaca superior to the superior part of the patella. For the BF muscle, the electrodes were placed at 50% on the line between the ischial tuberosity and the lateral epicondyle of the tibia. For the ST muscle, the electrodes were placed at 50% on the line between the ischial tuberosity and the medial epicondyle of the tibia. For the Glut-M muscle, the electrodes were placed at 50% on the line from the crista iliaca to the trochanter. The raw EMG signals were recorded at sampling rate of 1000 Hz and streamed via Bluetooth to a computer for further analysis. According to the European recommendations for surface EMG (SENIAM), the skin surface was shaved and cleaned with alcohol (70% Ethanol–C2H5OH) over the selected muscles [27]. Thereafter, the skin was gently abraded before electrode placement [27]. GRF and EMG data were synchronized using Nexus software (Oxford Metrics, Oxford, United Kingdom). A trial was considered successful if the dominant foot landed on the center of the force plate and if EMG signals were not contaminated upon visual examination. Leg dominance was assessed through a ball kicking test. For EMG analyses, the running cycle was divided into the following phases: first half of stance phase (early stance phase) and second half of stance phase (late stance phase) [30]. Using a handheld dynamometer, maximum voluntary isometric contraction (MVIC) was assessed for each recorded muscle to normalize EMG during running to MVIC. Appendix 1 describes the muscle-specific MVIC tests. All normalization procedures were realized in accordance with recommendations from Besomi et al. [31]. For example, the participants were encouraged to perform the tests at maximal effort [31]. Three test trials were conducted with 1–2 min rest periods in between tests [31]. For measuring MVIC, an isometric belt (where the joint is locked) was used (set for zero velocity) [31]. This instrument is important to control testing factors that can influence the output and facilitate the production of maximal contraction. The maximum value of the MVIC test was considered for normalization purposes [31].

2.4. Statistical analyses

Normal distribution of data was assessed and confirmed using the Shapiro–Wilk test. Between group comparisons were computed with an independent sample *t*-test. Effect sizes were calculated using the following equation: mean difference of groups/ pooled standard deviation. According to Cohen (34), $d< 0.50$ indicate small effects, $0.50 <d< 0.80$ indicate medium effects, and $d\geq 0.80$ indicate large effects. The significance level was set at $p < 0.05$. The statistical analyses were computed using SPSS (version 24, SPSS Inc., 8 Chicago, IL, United States).

3. Results

No statistically significant differences ($p > 0.05$) were found for running stance time between healthy controls (271.2 ± 9.8 ms) and COVID-19 individuals (272.4 ± 10.6 ms).

3.1. Running kinetics

The statistical analysis demonstrated higher peak vertical (Δ10%; $p = 0.029$; d=0.788) and medial (Δ88%; $p = 0.004$; d=1.119) ground reaction forces during push-off in COVID individuals compared with controls. Moreover, higher peak lateral ground reaction forces were found during heel contact (Δ106%; $p = 0.001$; d=1.536) in the COVID group (Table 2).

COVID-19 individuals showed a shorter time to reach the peak vertical (Δ110%; $p = 0.001$; d=3.779) and posterior ground reaction force (Δ45%; $p = 0.005$; d=1.099) during heel contact (Table 2). In addition, a shorter time to peak was also observed in the COVID group for lateral ground reaction force during push-off (Δ83%; $p = 0.048$; d=0.814).

3.2. Muscle activities

In terms of muscle activity during running, the COVID group exhibited higher Gas-M (Δ76%; $p = 0.007$, d=1.109) and lower VM activity (Δ36%; $p = 0.026$; d=0.811) at heel contact (Table 3).

The COVID group had higher Glut-M activity during the late stance phase (Δ35%; $p = 0.014$; d=0.919) and lower TA (Δ30%; $p = 0.009$; d=0.956), Gas-M (Δ37%; $p = 0.002$; d=1.182), and VM (Δ35%; $p = 0.007$; d=0.987) activity during the late stance phase (Table 4).

4. Discussion

The aim of this study was to compare kinetics and muscle activities during running in individuals who recovered from COVID-19 versus healthy controls.

The main findings of this study can be summarized as follows:

(i) COVID-19 individuals showed greater peak vertical and mediolateral GRFs during the heel contact and push-off phases.
(ii) The COVID group exhibited a shorter time to reach peak of vertical and posterior GRFs at heel contact.
(iii) COVID-19 individuals had greater Gas-M and lower VM activities during the early stance phase of running.
(iv) COVID-19 individuals experienced lower TA, Gas-M and VM activities and higher Glut-M activities in the late stance phase of running.

4.1. Running kinetics

Our results showed greater vertical and mediolateral GRFs in the COVID group compared with healthy controls. The results of this study confirm our research hypothesis. It has been demonstrated that during walking at different velocities (i.e., 0.54; 0.75; 1.15; 1.56 m/s), the abductor, vasti, and plantarflexor muscles make significantly larger contributions to mediolateral GRFs compared to the contributions of passive dynamics (i.e., gravity and velocity-related forces) [32]. On average, the above reported muscles contributed 92% of the total mediolateral GRFs across all examined walking speeds [32]. In this context, Liu et al. postulated that the abductors primarily support body mass by contributing large medial GRFs at all walking speeds while the vasti, gastrocnemius, and soleus contribute to propulsion and body mass support [33]. There is evidence of a statistically significant association between increased GRFs and rates of lower extremity injuries [34]. It has previously been shown for runners that high lateral GRFs during running result in overpronation [35] which may again cause overuse syndromes of the leg and the knee joint [36]. If signs of abnormally high lateral GRFs are observed in runners, it has been recommended to introduce injury preventive training programs such as balance and/or strength training to improve lower limbs alignment. Therefore, practitioners and therapists are advised to implement balance and/or strength training to improve lower limbs alignment and mediolateral control during dynamic movements in runners who recovered from COVID-19. Moreover, the COVID group showed shorter times to reach peak GRF values while running. Shorter time to reach peak values are associated with a higher rate of sustaining injuries such as stress fractures, articular soft tissue degeneration, and osteoarthritis [37]. It has been postulated that high

Table 2
Group-specific means and standard deviations of all examined running kinetic parameters.

Variable		Component	Healthy controls Means ± SDs	COVID-19 Means ± SDs	p-value (Cohen's d)
GRF (%BW)	FZ	FZ_{HC}	130.01 ± 31.25	144.15 ± 40.25	0.261 (0.395)
		FZ_{PO}	193.02 ± 23.73	213.33 ± 27.81	0.029 * (0.788)
	FY	FY_{HC}	31.99 ± 8.51	38.97 ± 17.68	0.152 (0.533)
		FY_{PO}	30.04 ± 6.05	29.79 ± 11.15	0.939 (0.029)
	FX	FX_{HC}	6.30 ± 3.43	13.007 ± 5.30	0.001 * (1.536)
		FX_{PO}	7.48 ± 3.89	14.09 ± 7.92	0.004 * (1.119)
TTP of GRF (%stance)	FZ	FZ_{HC}	11.76 ± 1.95	5.58 ± 1.32	0.001 * (3.779)
		FZ_{PO}	40.82 ± 6.33	40.52 ± 4.97	0.881 (0.053)
	FY	FY_{HC}	24.82 ± 4.46	17.11 ± 9.57	0.005 * (1.099)
		FY_{PO}	71.41 ± 1.90	72.58 ± 5.42	0.405 (0.319)
	FX	FY_{PO}	42.17 ± 13.79	33.05 ± 15.63	0.081 (0.619)
		FX_{HC}	15.76 ± 13.90	8.58 ± 3.72	0.048 * (0.814)
Free moment (%BW× height)	Negative peak	–	0.005 ± 0.003	0.005 ± 0.0033	0.660 (0.000)
	Positive peak	–	0.001 ± 0.00018	0.001 ± 0.00017	0.865 (0.000)

Note: FZHC, First peak vertical ground reaction force at heel contact; FZPO, Second peak vertical ground reaction force at push-off; FYHC, Braking reaction force; FYPO, Propulsion force; FXHC, Peak medial ground reaction force at heel contact; FXPO are consecutive negative peaks at the push-off phase, respectively. TTP, Time to reach peak.

Table 3
Group-specific means and standard deviations of normalized EMG activity (% maximum voluntary isometric contraction [MVIC])) of selected lower limbs muscles during the early stance phase.

Muscles	Healthy controls Means ± SDs	COVID-19 Means ± SDs	p-value (Cohen's d)
TA (%MVIC)	73.85 ± 16.68	83.12 ± 15.60	0.104 (0.574)
Gas-M (%MVIC)	24.47 ± 8.18	43.15 ± 25.49	0.007 * (1.109)
VL (%MVIC)	51.58 ± 22.70	64.24 ± 33.18	0.203 (0.453)
VM (%MVIC)	52.25 ± 14.08	38.25 ± 20.41	0.026 * (0.811)
RF (%MVIC)	41.93 ± 22.21	36.55 ± 16.82	0.431 (0.275)
BF (%MVIC)	34.13 ± 9.51	41.32 ± 15.51	0.113 (0.574)
ST (%MVIC)	40.25 ± 17.63	37.93 ± 17.40	0.702 (0.132)
Glut-M (%MVIC)	45.95 ± 15.55	44.12 ± 17.007	0.746 (0.112)

Note: TA, tibialis anterior; Gas-M, gastrocnemius medialis; VM, vastus medialis; VL, vastus lateralis; BF, biceps femoris; ST, semitendinosus; RF, rectus femoris; Glut-M, gluteus medius; MVIC, maximum voluntary isometric contraction.

Table 4
Group-specific means and standard deviations of normalized EMG activity (% maximum voluntary isometric contraction [MVIC]) of selected lower limbs muscles during the late stance phase.

Muscles	Healthy controls Means ± SDs	COVID-19 Means ± SDs	p-value (Cohen's d)
TA (%MVIC)	78.86 ± 19.05	60.41 ± 19.51	0.009 * (0.956)
Gas-M (%MVIC)	222.07 ± 54.76	161.95 ± 46.94	0.002 * (1.182)
VL (%MVIC)	113.77 ± 55.52	120.92 ± 41.84	0.659 (0.146)
VM (%MVIC)	172.23 ± 50.08	126.85 ± 41.84	0.007 * (0.987)
RF (%MVIC)	52.04 ± 23.79	42.35 ± 22.09	0.227 (0.422)
BF (%MVIC)	50.68 ± 25.73	48.81 ± 19.75	0.815 (0.082)
ST (%MVIC)	47.44 ± 20.97	39.74 ± 18.39	0.264 (0.391)
Glut-M (%MVIC)	74.35 ± 21.22	100.99 ± 36.70	0.014 * (0.919)

Note: TA, tibialis anterior; Gas-M, gastrocnemius medialis; VM, vastus medialis; VL, vastus lateralis; BF, biceps femoris; ST, semitendinosus; RF, rectus femoris; Glut-M, gluteus medius; MVIC, maximum voluntary isometric contraction.

GRFs and loading rates during running are caused by deficits in neuromuscular control (e.g., neuromuscular control of the quadriceps), as well as muscle weakness [38]. A previous study demonstrated that the braking force might be related to other important mechanical factors of performance [39]. For example, the braking force could be involved in the storage of elastic energy [40]. Moreover, fast sprinters have little time to produce high levels of GRFs which affords high force production due to the limited available time. Following the sign convention of Holden and Cavanagh (1991), positive free moments act to resist toeing out (adduction free moment) and negative free moments act to resist toeing in (abduction free moment) [15]. In this study, no significant between group differences were found for negative and positive free moment values during running.

4.2. *Muscle activities*

The COVID-19 group showed significantly higher activities for the Gas-M and significantly lower activities for the VM during the early stance phase compared with healthy controls. Muscles posterior to the ankle basically work as a unit and those anterior to the ankle joint work synergistically as another unit. Posterior calf muscles during walking function approximately during the middle 50% of the stance phase [41]. During running, this period of activity increases considerably, posterior calf muscles are active for approximately the first 80% of the stance phase and their activity begins in the last 25% of swing phase [41]. During running, the quadriceps muscle is activated during the last 20% of the swing phase and remains active for approximately the first 50% of the stance phase [41]. Athletes' running pattern is characterized by short ground contact times, and rapid dorsiflexion. This was done to cushion the impact of the body against the ground [41]. At the early stance, there is rapid knee flexion which also helps to absorb the impact of approximately ~1.5–3 times body mass at the time of ground contact [41]. It has previously been shown that changing the afferent information of the plantar surface during running can alter lower limbs muscle activity [42]. Therefore, altered muscle activation pattern during running in individuals with COVID-19 was occurred that may be due to altered afferent information during ground contact [43]. The quadriceps femoris and TA muscles were involved in shock attenuation during early stance phase of walking and running [44].

The COVID-19 group showed significantly higher Glut-M activity and lower TA, Gas-M and VM activities during the late stance phase. A previous study indicated that muscle involvement in COVID-19 infected subjects is most likely related to functional impairment rather than tissue damage [10]. Our results support this hypothesis. A previous study [45] reported that excessive rear-foot eversion during the stance phase of gait appears to be responsible for an increased internal rotation of the tibia with respect to the talus. Moreover, due to joint coupling the hip may rotate internally, thereby increasing hip adduction and the dynamic Q angle [45]. During walking and running, the Glut-Med acts as hip abductor to stabilize the pelvis as the contralateral leg swings through [46]. Weakness of the Glut-Med may result in adverse changes in kinematics [47] and a concomitant increase in risk of injury [48]. Therefore, an increase in Glut-M activity may enhance hip abduction and decrease rear-foot eversion.

This study has a few limitations that warrant discussion. First, a relatively small cohort was included in this study. Given that we examined participants with a prior COVID-19 infection, it was difficult to enroll more individuals at the time of the study. Future research should replicate our study design with a larger sample to confirm or question our findings. Second, we examined adults with COVID-19 versus age-matched healthy controls. Therefore, our findings are specific to the population under investigation. More research is needed to establish whether our findings can be translated to different population groups.

5. Conclusions

Running kinetics and muscle activities differ between individuals who recovered from COVID-19 compared with healthy controls. Therefore, a specific rehabilitation protocol is needed for COVID-19 individuals to recondition their running mechanics.

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Conflict of interest statement

The authors report no declarations of interest.

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