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Adaptations in single-leg hop biomechanics following anterior cruciate ligament reconstruction

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Abstract When a patient performs a clinically normal hop test based on distance, it cannot be assumed that the biomechanics are similar between limbs. The objective was to compare takeoff and landing biomechanics between legs in patients who have undergone anterior cruciate ligament reconstruction. Kinematics and ground reaction forces were recorded as 13 patients performed the single-leg hop on each leg. Distance hopped, joint range of motion, peak joint kinetics and the peak total extensor moment were compared between legs during both takeoff and landing. Average hop distance ratio (involved/noninvolved) was 93 ± 4%. Compared to the noninvolved side, knee motion during takeoff on the involved side was significantly reduced ($P = 0.008$). Peak moments and powers on the involved side were lower at the knee and higher at the ankle and hip compared with the noninvolved side (Side by Joint $P = 0.011$; $P = 0.003$, respectively). The peak total extensor moment was not different between legs ($P = 0.305$) despite a decrease in knee moment and increases in ankle and hip moments (Side by Joint $P = 0.015$). During landing, knee motion was reduced ($P = 0.043$), and peak power absorbed was decreased at the knee and hip and increased at the ankle on the involved side compared to the noninvolved side ($P = 0.003$). The compensations by other joints may indicate protective adaptations to avoid overloading the reconstructed knee.

Keywords Knee · Ankle · Hip · Landing · Takeoff · Compensations

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Introduction

Quadriceps weakness is a common complication following anterior cruciate ligament (ACL) reconstruction [11, 25]. During rehabilitation, the single-leg hop for distance is often used to test knee function following ACL reconstruction [10, 13, 14, 21]. A side-to-side ratio (distance hopped on involved leg/distance hopped on uninvolved leg) of 85% or greater is considered normal and often used as a milestone for advancement to the next stage of rehabilitation [3, 13].

Given that the single-leg hop test is a multi-segmental coordinated movement, it is possible that compensations can occur between joints to maintain performance where a single joint or muscle has been compromised by injury. Therefore, while a patient may be able to perform a clinically normal hop test based on hop distance (within 85% of the noninvolved side), it cannot be assumed that the performance of each joint is similar between limbs. In previous research examining ACL-deficient patients, Gauffin and Tropp [8] demonstrated that the hip and ankle compensate for weakness at the knee in order to produce similar levels of performance (hop distance) between the involved and noninvolved legs. It is currently not known if such adaptations are evident after ACL reconstruction and rehabilitation.

Landing from a jump is also regarded as a functional activity which places high demand on the lower extremity to absorb ground reaction forces [5, 12, 16]. Augustsson et al. [2] observed greater knee moments and powers during single-leg hop landings compared to takeoff and suggested that comparing a patient's ability to perform single-leg landings on the involved leg versus the noninvolved leg may provide a more comprehensive assessment of functional abilities than measuring hop distance. Risberg et al. [19] assessed landing biomechanics in ACL-deficient patients and demonstrated a reduction in performance at the involved knee that was compensated for by increased performance at the ankle and hip. Further, these authors suggest that the functional deficits and compensation strategies may normalize following ACL reconstruction. Gokeler et al. [9] examined the landing biomechanics of patients 6 months following ACL reconstruction and found that this adaptation (reduced knee moment and increased ankle and hip moments) still remained. Patients in this study also exhibited an abnormal (<85%) hop ratio, which could be indicative of residual quadriceps weakness on the involved side. Orishimo and Kremenic [15] demonstrated that weakness due to thigh muscle fatigue can induce similar compensatory landing adaptations in healthy individuals with normal hop ratios. Therefore, by considering only the distance hopped, residual quadriceps weakness following ACL reconstruction and rehabilitation may be masked by compensatory adaptations during both the takeoff and landing phases of this dynamic exercise.

Identifying and understanding side-to-side differences in the performance of the individual joints during this test will allow standard physical therapy protocols to be modified to address and possibly eliminate functional deficits. The purpose of this study was to compare joint ranges of motion, joint moments and joint powers in the involved and noninvolved legs of patients who have had an ACL reconstruction as they performed the single-leg hop test. We hypothesized that the ACL-reconstructed knee would demonstrate lower peak moment and power in both takeoff and landing than the uninvolved knee, with compensations for this occurring at the ankle and hip in order to maintain hop performance.

Materials and methods

Thirteen patients who had undergone an ACL reconstruction (9 M, 4 F; Height 174.5 ± 9.4 cm, Mass 72.3 kg ± 11.9 kg, Age 33 ± 10 years) performed a maximal-effort single-leg horizontal hop off of and onto a force plate using both the involved and noninvolved legs. For inclusion in this study, subjects had to be undergoing rehabilitation at our physical therapy clinic following a bone-patellar tendon-bone ACL reconstruction, with no history of injury to their uninvolved leg. Once subjects reached the point in their rehabilitation that they were able to successfully perform a clinically normal single-leg hop test on the involved leg (85% of the distance hopped on the uninvolved leg), they were tested for this study (a range of 4–12 months following ACL reconstruction surgery). As some patients progressed through rehabilitation at a faster rate than others, we decided to test each patient as soon as they reached the same clinical milestone, as opposed to the same follow-up time. This ensured that all patients had similar functional abilities at the time of testing. Prior to participation, subjects provided informed consent in accordance with the Institutional Review Board.

Subjects performed three takeoff trials followed by three landing trials. For the takeoff trials, subjects started in single-leg stance with their foot in the center of the force plate. They then performed a single-leg hop for maximal horizontal distance, landing on the same leg on the laboratory floor. There were no restrictions of upper extremity movement. Hop distance was measured from the toe in the starting position to the heel at landing. The average distance of the three takeoff trials was measured from the center of the force plate and marked as the starting point for the landing trials. Subjects started in single-leg stance with their toe at the starting point and performed three single-leg hops onto the force plate. Trials in which the foot did not land completely on the force plate were discarded, and the trial was repeated.

Reflective markers were placed over the calcaneous, first and fifth metatarsals, medial and lateral malleoli, anterior shank, medial and lateral femoral condyles, anterior thigh, greater trochanter, sacrum and anterior superior iliac spine of the dominant leg and the greater trochanter and anterior superior iliac spine of the contralateral leg. Marker positions were collected at 60 Hz using five infrared cameras (Qtrac, Qualisys, Gothenburg, Sweden). The motion data were then filtered with a fourth-order Butterworth low-pass filter with a cutoff frequency of 10 Hz in order to eliminate any high frequency noise. Ground reaction forces (GRF) were recorded at 960 Hz with a multi-component force plate (Kistler Instrument Corp., Amherst, NY, USA).

Each takeoff was defined from the minimum vertical position of the sacrum marker to the instant the subject left the force plate. The vertical position of the sacrum marker was used as an approximation of the height of the subject's center of mass. Thus, the minimum vertical position of the sacrum marker was interpreted to be the lowest point of the center of mass before initiation of the hop. Landings were defined from initial contact with the force plate to the minimum vertical position of the subject's sacrum marker after impact. In this case, the minimum vertical position of the sacrum marker was interpreted to be the point at which the vertical velocity of the center of mass reached zero, signaling the end of the impact phase of the landing.

Sagittal plane angles, moments and powers were calculated for the ankle, knee and hip using specialized computer software (Visual 3D, C-Motion, Inc., Rockville, MD, USA). Ankle dorsi flexion, knee flexion and hip flexion angles were defined as positive values. Additionally, hip and knee extensor as well as ankle plantar flexor internal moments were assigned to be positive. Previous experiments performed in our laboratory [15] have shown that with 80% power, a 20% difference joint kinematics and kinetics can be detected. Anterior shear forces at the knee were also calculated, as the ACL is the primary static restraint to these forces [4]. The total extensor moment was calculated by adding the net moments at the ankle, knee and hip throughout the length of each trial [23, 24]. The maximum value of the total extensor moment was determined, and the contribution of each joint to that maximum value was calculated. All joint moments and powers were normalized to body mass. The magnitude of the ground reaction force was also recorded, in order to compare takeoff and landing forces between the involved and noninvolved legs.

Statistical analysis

A paired *t* test was used to determine if there was a difference in distance hopped between the involved and noninvolved legs. Repeated measures analyses of variance (Side × Joint) were performed to assess the effect of ACL reconstruction on the range of motion, peak extension moments and peak powers at each joint during both the takeoff and landing phases. Additional analyses of variance (Side × Joint) were performed to assess differences in joint moments measured at the time of peak total extensor moment during takeoffs and landings. When significant main effects or interactions were found, paired *t* tests were used to compare variables between the involved and noninvolved legs. Bonferroni corrections were applied to post hoc comparisons where applicable. Additional paired *t* tests were used to assess differences in peak ground reaction force (overall magnitude, as well as vertical and anterior/posterior components) between the involved and noninvolved legs during both takeoff and landing. $P < 0.05$ was considered significant.

Results

The mean testing time after surgery was 7.2 ± 2.7 months (range 4–12 months). Although all subjects hopped further on the noninvolved leg (145.2 ± 30.6 cm noninvolved; 135.8 ± 31.9 cm involved; $P < 0.001$), hop ratios were greater than 85% and thus in the clinically normal range (87–99%; mean 93%).

Takeoff

Ensemble averages of joint motions, moments and powers for the ankle, knee and hip are shown for the takeoff phase of the hop for both involved and noninvolved lower extremities in Fig. 1, with corresponding data summarized in Table 1.

On the involved limb, the range of motion at each joint (ankle, knee and hip) was decreased compared to the noninvolved side ($P = 0.006$). Subjects achieved less knee flexion on the involved side at the start of takeoff ($P = 0.025$) and had a greater amount of knee flexion at the instant they left the ground ($P = 0.033$).

The peak resultant ground reaction force during takeoff was not different between the involved and

Fig. 1 Ensemble kinematic and kinetic profiles for 13 subjects during takeoff for the uninvolved (*solid lines*) and involved (*dash-dot lines*) lower extremities

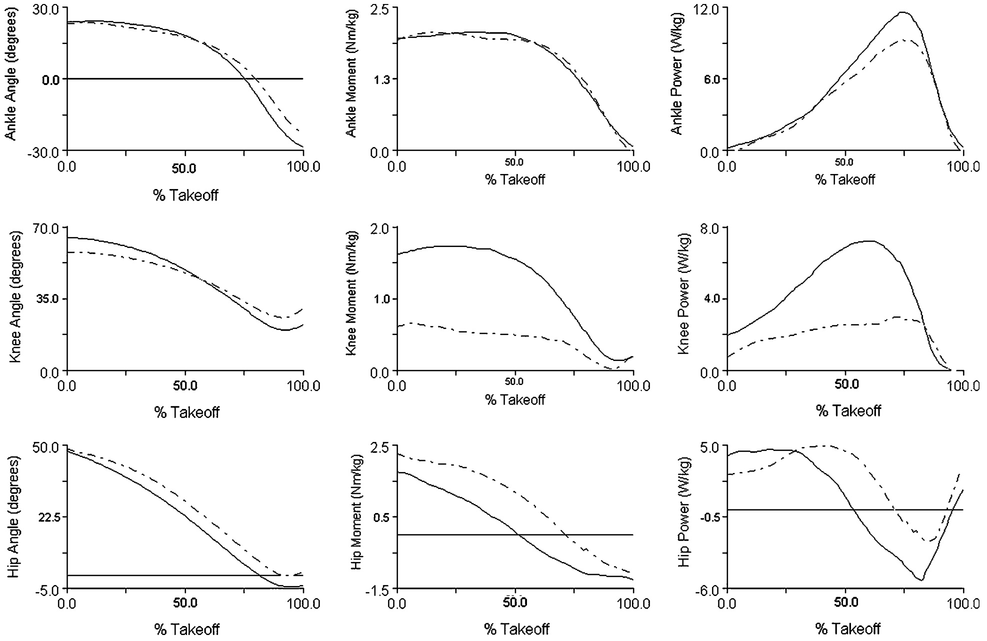

Table 1 Mean kinematic and kinetic variables (SD) for the ankle, knee and hip during takeoff on the involved and noninvolved legs

Variable	Involved	Noninvolved
Range of motion (°)	Side $P = 0.006$	
Ankle	49.1 (11.1)	53.7 (6.5)
Knee	35.6 (14.2)	48.1 (14.4)*
Hip	48.1 (22.6)	56.2 (19.6)
Peak GRF (BW)		
Overall magnitude	1.7 (0.3)	2.0 (0.3)
Anterior	0.5 (0.2)	0.5 (0.2)
Vertical	1.7 (0.3)	1.9 (0.3)
Peak extension moment (Nm/kg)	Side × Joint $P = 0.011$	
Ankle	2.6 (0.6)	2.3 (0.5)
Knee	1.2 (0.9)	2.0 (0.9)*
Hip	2.5 (1.2)	1.8 (1.1)
Peak power (W/kg)	Side × Joint $P = 0.003$	
Ankle	13.7 (5.5)	13.2 (4.6)
Knee	6.4 (4.3)	10.4 (5.1)*
Hip	8.2 (3.9)	6.8 (4.2)
Peak total extensor moment (Nm/kg)	5.1 (0.8)	5.3 (1.4)
Moment at peak total extensor moment (Nm/kg)	Side × Joint $P = 0.015$	
Ankle	2.2 (0.7)	1.8 (0.9)
Knee	0.8 (1.4)	1.9 (0.9)*
Hip	2.1 (1.1)	1.6 (1.0)

* Significant difference between involved and noninvolved legs ($P < 0.05$)

noninvolved legs. Additionally, no difference was detected in the peak anterior or vertical ground reaction force components.

Compared to the noninvolved side, peak knee extension moment on the involved side was 40% lower while peak ankle and hip extension moments were 13% and 38% higher, respectively (Side × Joint $P = 0.011$). Peak power generated at the knee was 38% lower on the involved versus the noninvolved side while peak power at the ankle and hip were 4% and 21% higher, respectively (Side × Joint $P = 0.003$).

Knee extension moment at the time of peak total extensor moment was 58% lower on the involved versus noninvolved side and the ankle and hip extension moments at this time were 22% and 31% higher, respectively (Side × Joint $P = 0.015$). No significant difference in the peak total extensor moment was found between the involved and noninvolved legs. Additionally, no difference in peak anterior shear force at the knee was found (0.87 ± 0.30 BW involved; 0.97 ± 0.25 BW noninvolved).

Landing

Ensemble averages of joint motions, moments and powers for the ankle, knee and hip are shown for the landing phase of the hop for both involved and noninvolved lower extremities in Fig. 2, with corresponding data summarized in Table 2.

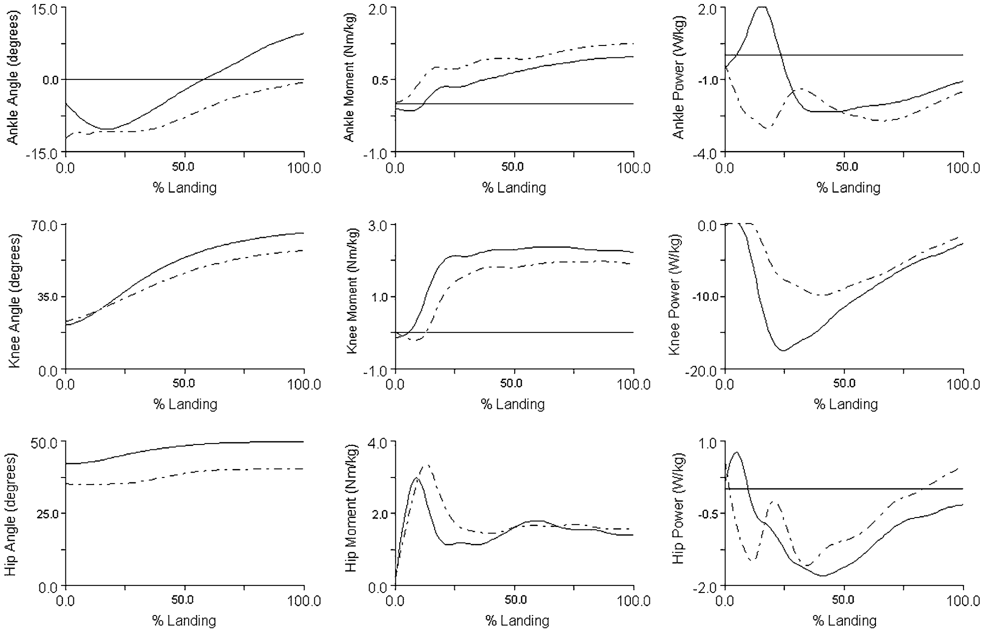

Fig. 2 Ensemble kinematic and kinetic profiles for 13 subjects during landing for the uninvolved (*solid lines*) and involved (*dash-dot lines*) lower extremities

Table 2 Mean kinematic and kinetic variables (SD) for the ankle, knee and hip during landing on the involved and noninvolved legs

Variable	Involved	Noninvolved
Range of motion (°)	Side $P = 0.039$	
Ankle	22.3 (13.2)	25.0 (7.5)
Knee	35.7 (8.2)	43.4 (12.3)*
Hip	10.5 (5.0)	12.3 (4.9)
Peak GRF (BW)		
Overall magnitude	4.5 (1.6)	5.1 (1.4)
Posterior	1.7 (0.8)	1.9 (0.7)
Vertical	4.2 (1.5)	4.7 (1.3)
Peak extension moment (Nm/kg)	Side × Joint $P = 0.766$	
Ankle	1.8 (0.9)	1.3 (0.7)
Knee	3.3 (1.7)	3.5 (1.1)
Hip	5.5 (3.8)	5.3 (2.1)
Peak power (W/kg)	Side × Joint $P = 0.003$	
Ankle	−7.0 (5.4)	−5.2 (2.4)
Knee	−16.2 (8.0)	−28.4 (10.8)*
Hip	−8.0 (7.7)	−9.9 (4.7)
Peak total extensor moment (Nm/kg)	6.1 (2.0)	6.6 (2.1)
Moment at peak total extensor moment (Nm/kg)	Side × Joint $P = 0.120$	
Ankle	1.4 (0.8)	0.6 (0.7)
Knee	1.5 (1.3)	1.7 (1.0)
Hip	3.2 (2.2)	4.3 (2.5)

* Significant difference between involved and noninvolved legs ($P < 0.05$)

Similar to the takeoff phase, ankle, knee and hip ranges of motion were decreased during landing on the involved limb compared to the noninvolved side (Main Effect of Side, $P = 0.039$).

The peak resultant ground reaction force during landing was not different between the involved and noninvolved legs. Peak posterior and vertical ground reaction force components were also not different between the involved and noninvolved legs.

Peak moments at the knee, ankle and hip were not significantly different in the involved leg compared to the noninvolved side. Peak power absorption during landing on the involved versus the noninvolved side was 43% lower at the knee, 19% lower at the hip and 42% higher at the ankle (Side × Joint $P = 0.003$). No significant difference was found in the maximum total extensor moment in the involved and noninvolved legs. There was also no difference between the involved and noninvolved sides for the ankle, knee and hip moments at the maximum total extensor moment. Similarly, no difference in peak anterior shear force at the knee was found (1.0 ± 0.4 BW involved; 1.1 ± 0.3 BW noninvolved).

Discussion

The principle finding of this study was that patients continued to exhibit impairment in the involved knee despite achieving clinically normal hop ratios. During take-off, knee range of motion on the involved side was 25% lower compared to the noninvolved side. This limited range over which force could be generated resulted in a 40% reduction in peak knee moment and a 38% reduction in peak knee power on the involved side. These deficits were primarily compensated for by a 38% and a 21% greater peak moment and power at the hip. Knee range of motion on the involved side was reduced during landing by 18%. As a result of this limited range for energy dissipation, peak power absorption at the knee was 43% lower on the involved versus the noninvolved side and was compensated for by a 42% increase in power absorption at the ankle. This pattern of increased performance at the ankle on the involved side is similar to the landing adaptation that Orishimo and Kremenic [15] demonstrated following thigh muscle fatigue and is consistent with a "softer" landing. The senior author (SJN) has noted clinically that after ACL reconstruction, patients tend to land more softly on the involved side regardless of how far they jump.

The apparent deficit at the knee and compensations at the ankle and hip found in the current study indicate that measuring only the distance hopped may not be an adequate test of knee function in patients after ACL reconstruction. Although side-to-side hop distance ratios are frequently reported for patients following ACL reconstruction, these measurements have not been strongly correlated with measures of isokinetic quadriceps strength ($r = 0.4$–0.6) [7, 17, 22]. The findings of the current study seem to suggest that single-leg hop performance is a measurement of total lower extremity function and may not be indicative of performance at a particular joint. Further, Augustsson and Thomee [1] found only moderate correlation ($r = 0.51$) between vertical jump height and a more functional, closed-chain assessment of lower extremity strength (barbell squat). Therefore, biomechanical analysis of functional exercises, such as the single-leg hop, may be necessary for the assessment of function at each joint and may be more helpful in identifying deficits due to injury or surgery than measuring overall performance (distance hopped or vertical jump height).

Contrary to the assertion by Risberg et al. [19] that the biomechanical adaptations typically observed in high-functioning ACL-deficient patients should resolve after restoring the mechanical stability provided by the ACL, the results of the current study seem to indicate that functional knee impairment and adaptive compensations still remain following ACL reconstruction and rehabilitation. It is not known, however, whether this adaptation normalizes over time or remains at longer follow-up. Further, the effect of the ACL reconstruction surgery, itself, on the neuromuscular function of the lower extremity is not known and warrants additional investigation.

Ernst et al. [6] examined ACL-reconstructed patients performing vertical jumps and found similar adaptations to those seen here. Knee extension moment was reduced in the involved leg compared to the noninvolved leg. However, no difference in the total extension moment (the sum of the maximum extension moments measured at each joint) was found between legs. Because this quantity was not different between legs, it was assumed that the moments at the ankle and/or hip must have increased in order to compensate for the deficit at the knee in the involved leg. While subjects in the Ernst et al. study demonstrated a similar adaptation to that found in the current study, it is not clear whether the overall performance (i.e., hop height or ground reaction force) on each leg was equivalent. Hence, it is not known whether they were considered to be clinically normal or still displayed a functional deficit.

Anteriorly-directed shear forces on the proximal tibia have been shown to directly load the ACL [4]. In the present study, there was no apparent difference between the involved and noninvolved limbs in anterior shear forces at the knee during both takeoff and landing. Therefore, the lower moment and power at the knee during takeoff and the lower power absorption at the knee during landing may be adaptations to avoid excessive anterior shear. Sell et al. [20] found that posterior ground reaction force and knee extension moment were highly predictive of anterior tibial shear force during a jump-stop landing. The results of the current study have shown no difference in posterior ground reaction force or peak knee extension moment between the involved and noninvolved legs during landings. This seems to indicate that following ACL reconstruction, altered biomechanics may be needed in order to maintain similar knee loading conditions between the involved and noninvolved legs.

There are limitations in this study that warrant mention. First, the camera system used to record kinematic data operated at a sampling rate of 60 Hz. A higher sampling rate would provide more frames from the beginning to the end of each trial to be analyzed resulting in more detailed kinematic and kinetic profiles for each joint. Secondly, as suggested by Pfeifer and Banzer [18], assessing the EMG patterns of the relevant musculature during functional tests may enhance the ability to detect possible deficits due to injury or surgery. Comparison of quadriceps, gluteal and calf muscle activity between the involved and noninvolved legs may be helpful in explaining the deficits at the knee and compensatory adaptations observed at the ankle and hip. Lastly, quadriceps strength in the involved and noninvolved sides was not assessed at the time of biomechanical testing. Correlation of isometric or isokinetic quadriceps strength with knee performance measured during the single-leg hop test may provide a stronger relationship than previous studies which used overall hop distance.

Conclusion

Our biomechanical analysis of the single-leg hop revealed significant differences in joint kinetics between the involved and noninvolved legs despite the fact that all patients in this study were deemed clinically normal based on hop distance. Clinicians should be aware that hop ratios based on distance can be deceiving because equivalent performances are not necessarily indicative of similar biomechanics between the involved and noninvolved legs. During takeoff, decreased moment and power production at the involved knee were primarily compensated for by higher moments and power at the hip. During landing, decreased power absorption at the involved knee was compensated for by greater power absorption at the ankle. Additionally, the presence of these adaptations after ACL reconstruction and rehabilitation seems to indicate that restoring the mechanical stability provided by the ACL may not restore normal joint kinematics or kinetics during high-demand activities. Further, these hip and ankle compensation strategies may be indicative of a protective adaptation to avoid excessive anterior shear on the reconstructed knee. Future research is needed to investigate if these adaptations are reversed by fully restoring quadriceps strength.

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