Biomechanical laboratory analyses have previously been utilised to identify certain movement patterns which characterise participants suffering from recurrence after acute lateral ankle sprain (LAS) injury.1–3 Typically, these movement patterns, and the motor control strategies that underlies them, are evaluated using functional tasks analogous to activity based manoeuvres which have a tendency to be injurious to their participants.4 For example, the drop vertical jump (DVJ) task has consistently been used to identify several movement patterns contingent with anterior cruciate ligament (ACL) injury.5–7 As a task, the advantage of the DVJ is that it demands inter-limb synchrony to fulfil both predictive [pre-initial contact (IC)] and reactive (post-IC) actions of neuromuscular control8 in achieving dynamic balance and a performance output of maximal jump height.

In instances of injury, the sensorimotor system is challenged to balance the performance output of the DVJ whilst maintaining the integrity of the motor apparatus.4,9,10 As such, kinematic,9 kinetic,6 and inter-limb symmetry7 variables have all been quantified during both the drop jump (phase 1) and/or the drop and landing (phase 2) components of the DVJ to elucidate task-specific movement compromises predictive and/or consequent of ACL injury.4,9,10 Similarly, and because LAS is a significant injury risk in activities with repetitive jumping and rebounding movements,10 biomechanical analyses have adopted DVJ based tasks in a comparable manner to the ACL literature in identifying those movement patterns which characterise individuals experiencing recurrence following their initial LAS.1–3 However, in contrast to the ACL literature, key predictors of long-term chronicity following LAS have yet to be identified. Herein lies a prominent gap in the literature, and in light of the potential for an acute LAS to degrade into the array of chronic sequelae collectively termed ‘chronic ankle instability’ (CAI),11–14 priority should be placed in its mitigation.

It has been hypothesised that recovery following LAS is dependent on the emergence of new coordination strategies of neuromuscular control, and it is the success or failure of these strategies that manifests in ‘coper’ or CAI status respectively.15 However, because individuals can only be classified as being copers or as having CAI a minimum of one year following injury,11,15 greater certainty as to the key contributors to recovery can only be gained by evaluating individuals ‘on course’ to their outcome, thus culminating in a set of DVJ-based biomechanical prediction rules for recovery. The current investigation is part of a series designed to identify such predictors. In this exploratory analysis, lower extremity movement patterns (kinematics), motor control (moment of force profiles), landing force and symmetry analyses were combined to evaluate DVJ task strategies in a group with a 6-month history of first-time LAS injury. Our experimental objective was to identify movement and motor control patterns which are likely to be predictive of long-term outcome following LAS; this experiment stands to inform our choice of variables for future longitudinal analyses.
METHODS

Design: Case-Control Study
Level of Evidence: III

Fifty-one participants (thirty-five males and sixteen females; age = 23.14 ± 4.45 years; height = 1.74 ± 0.09 m; body mass = 74.5 ± 14.1 kg) were recruited from a local hospital Emergency Department (ED) within 2-weeks of sustaining a first-time acute LAS injury; this manuscript pertains to data collected 6-months following recruitment from the ED. Another group of twenty control participants (fifteen males and five females, age = 22.6 ± 1.7 years; height = 1.73 ± 0.1 m; body mass = 71.4 ± 11.29 kg) with no history of prior LAS were recruited from the hospital catchment area population using posters to act as a control group.

The following exclusion criteria were applied to all participants at the time of recruitment (for both limbs, where applicable): (1) no previous history of ankle sprain injury (excluding the recent episode for the injured group); (2) no other lower extremity injury in the last 6-months; (3) no history of ankle fracture; (4) no previous history of major lower limb surgery; (5) no history of neurological disease, vestibular or visual disturbance or any other pathology that would impair their motor performance. All participants completed the Cumberland Ankle Instability Tool (CAIT)17 and the activities of daily living and sports subscales of the Foot and Ankle Ability Measure (FAAM) and FAAM-sport18 to assess overall ankle joint function and patient reported functional ability, respectively, on arrival to the laboratory.11–14

The experimental protocol was approved by the institution’s ethical review board and informed written consent was acquired from each participant prior to testing.

Following completion of the questionnaires, participants were instrumented with twenty-two infrared markers as part of the Codamotion (CODA) bilateral lower limb gait set-up (Charnwood Dynamics Ltd, Leicestershire, UK). Following the collection of the anthropometric measures required for the calculation of internal joint centres at the hip, knee and ankle joints, lower limb markers and wands were attached as described by Monaghan et al.19 For each subject, an initial neutral stance trial was acquired to function as a reference position for kinematic analyses and to align the subject with the laboratory coordinate system.20 Participants then completed a DVJ practice period during which they familiarised themselves with experimental procedures. Specifically, participants completed up to five practice trials whereupon they established confidence in their ability to complete the DVJ, and one researcher (C.D) determined that their technique conformed to pre-determined protocols. Then, following a two-minute rest period, they completed three ‘test’ trials during which data were acquired. The DVJ protocol utilised for the current study has been described previously.5 During the three test trials, kinematic data were acquired at 250 Hz and kinetic data at 1000 Hz for each limb. This was completed using three Codamotion cx1 units and two fully integrated AMTI (Watertown, MA) walkway embedded force-plates, respectively. The CODA units were time synchronized with the force-plates. Kinetic and kinematic data were passed through a fourth-order zero phase Butterworth low-pass digital filter with 20Hz and 6-Hz cut-off frequencies, respectively.21

Kinematic and kinetic data were acquired and exported from the Codamotion software to Microsoft Excel file format for further analysis. 3-dimensional hip, knee and ankle internal joint moments were calculated in time-averaged profiles, with subsequent calculation of group mean profiles. All moments were reported as internal joint moments derived from the ground reaction force (GRF) data created during contact with the force-plates. All time-averaged profiles were plotted during the period from 200-ms pre-initial contact (IC) to 200-ms post-IC for the first and second phases of the DVJ.

The rate of impact modulation (RIM) of the vertical GRF was calculated for each phase of the DVJ for each limb as the peak GRF normalised to bodyweight (BW) divided by the time from IC to peak vertical GRF22 (BW/sec). The RIM was averaged accordingly and group mean profiles were calculated. Symmetry between temporal waveform data (angular displacement and moment-of-force profiles) was analysed using an eigenvector approach. A ‘trend symmetry’ (TS) parameter was calculated to compare the time-normalised data for right and left limbs separately during phase 1 and phase 2 of the DVJ for the LAS and control groups. The advantage of the TS calculation is that it allows for the determination of symmetry between non-discrete, waveform data. To calculate the TS of a given combination of waveforms, a matrix (M) is formed by pairs of data-points derived from the left and right legs. A ‘singular value decomposition’ is then applied to M, and from this, a series of eigenvectors are derived. Each row of M is then rotated by the angle formed between the eigenvector and the X-axis so that the points lie around the X-axis. The variability of the points is subsequently calculated along the X and Y-axes, whereby Y-axis variability is the variability about the eigenvector and X-axis variability is the variability along the eigenvector. Finally, the trend symmetry value is determined by taking the ratio of the variability about the eigenvector to the variability along the eigenvector. This is expressed as a percent where 0% indicates perfect symmetry between the two waveforms.23 Trend symmetry was performed using a sliding window approach: data samples were analysed for symmetry in groups of 50 samples with a window overlap of 50%. This resulted in three separate trend symmetry windows to assess the preparatory,24 and reactive25,26 activities of each landing event, in addition to IC; window 1 analysed from 200 ms pre-IC to IC, window 2 analysed from 100 ms pre-IC to 100 ms post-IC and window 3 analysed from IC to 200 ms post IC.

TS was calculated separately for each trial of the DVJ and averaged across the three trials for each participant. Group mean profiles were then calculated.

A symmetry angle (SA) calculation27 was utilised to evaluate the inter-limb RIM symmetry for each individual subject over each phase of a DVJ trial, with subsequent calculation of group means. A SA value of 0% between matched points indicates perfect symmetry, while 100% indicates that the two values are equal and opposite.27

Finally, the vertical jump height (m) achieved between phases 1 and 2 of the DVJ was calculated as a measure of task performance using the time of flight method28 for LAS and control groups, with subsequent calculation of group mean profiles.

The average of each subjects’ three trials for all variables was analysed (i.e., LAS vs control). For the LAS group, limbs were labelled as “involved” and “uninvolved” depending on which limb they injured at the time of recruitment; in all cases, the involved (injured) limb was compared to side-
matched limbs in the control group, such that an equal proportion of right and left limbs were labelled as “involved” and “uninvolved” in each group.

A series of independent samples t-tests for each data point of the time-averaged 3D kinematic and sagittal plane kinetic profiles were undertaken to compare the movement and motor control patterns exhibited by the LAS and control groups during the DVJ task. The significance level for these analyses was set a priori at \( p < 0.05 \).

Next, independent samples t-tests for group (LAS vs control) RIM mean profiles for each phase of the DVJ for each limb were undertaken. The significance level for this analysis was set a priori at a bonferroni adjusted alpha level of \( p < 0.025 \) (involved and uninvolved limbs).

To determine whether these coordination and motor control strategies would be contingent with disparities in inter-limb symmetry, independent samples t-tests were undertaken for group angular displacement and support moment profile TS windows for each phase of the DVJ. The significance level for these analyses were adjusted for multiple tests using the Benjamini-Hochberg method for false discovery rate \((<5\%)\) separately for kinetic and kinematic data, each with two levels (involved and uninvolved limbs). Independent samples t-tests for group (LAS vs control) RIM SA profiles for each phase of the DVJ were also undertaken. The significance level for this analysis was set a priori at \( p < 0.025 \). All data were analyzed using Predictive Analytics Software (Version 18, SPSS Inc., Chicago, IL).

RESULTS

Questionnaire scores for LAS and control participants are detailed in table 1.

Time-averaged 3-dimensional kinematic profiles revealed a number of between-groups differences for both phase 1 and phase 2 of the DVJ. Lower extremity sagittal plane and frontal plane ankle kinematic profiles for phases 1 and 2 of the DVJ are detailed in Figure 1.

Time-averaged sagittal plane moment-of-force profiles also revealed a number of between-groups differences for both phase 1 and phase 2 of the DVJ. Sagittal plane moment-of-force profiles for phases 1 and 2 of the DVJ are detailed in Figure 2.

There was no significant difference in RIM between LAS and control participants for phase 1 or phase 2 of the DVJ for either limb. RIM during both phases of the DVJ for LAS and control groups are detailed in Table 2.

TS analyses of kinematic and kinetic data revealed that the LAS group displayed greater inter-limb asymmetry in the hip moment of force profile during phase 1 of the DVJ in the third time window (from IC to 200ms post-IC). TS values for all kinetic data for LAS and control groups are detailed in Table 3. LAS participants displayed increased RIM asymmetry compared to control participants during both phase 1 and phase 2 of the DVJ (Table 2).

There was no significant difference in jump height scores between the LAS \((0.16 \pm 0.5 \text{ m})\) and control \((0.18 \pm 0.9 \text{ m})\) groups \((t(17.32) = -0.60, p = 0.56)\).

DISCUSSION

The novelty of this exploratory study is that we have identified movement patterns unique to individuals with a 6-month history of first-time LAS and also revealed some potential consistencies in the coordination strategies adopted by this cohort and those exhibited by individuals with CAI performing similar tasks. Specifically, LAS participants in the current study displayed a reduction in ankle joint plantar-flexion on their involved limb during phase 2 of the DVJ and an increase in inter-limb asymmetries of RIM during both phase 1 and phase 2. Furthermore, they displayed increased moment of force profile asymmetries at the hip in the ground contact phase component of phase 1 of the DVJ. The increase in ankle inversion on their involved limb during phase 2 of the DVJ has previously been observed in the CAI literature during a stop-jump task, a drop landing task and a lateral hopping task.

The potential for inversion laxity to coincide with damage to the calcaneofibular ligament in LAS participants, thus resulting in greater frontal plane motion, has repeatedly been implicated in the greater tendency of these individuals towards inversion injury. It has been theorised that the introduction of uncontrollable frontal plane motion breaks the normal boundaries of the “safe” window of ankle/foot positioning at IC, thus leading to re-injury. In contrast, the preparatory reduction in ankle plantar flexion in the LAS cohort could potentially be considered an active, adaptive strategy to limit the placement of the ankle joint further into a position of increased vulnerability. With

<table>
<thead>
<tr>
<th>Group</th>
<th>CAIT (/30) ([95% \text{CI}: 21.22 \text{ to } 23.93])</th>
<th>FAAMadl (%) ([95% \text{CI}: 94.54 \text{ to } 97.27])</th>
<th>FAAMsport (%) ([95% \text{CI}: 81.04 \text{ to } 88.36])</th>
</tr>
</thead>
<tbody>
<tr>
<td>LAS</td>
<td>22.58 (\pm 5.53) ([95% \text{CI}: 21.22 \text{ to } 23.93])</td>
<td>95.91 (\pm 5.57) ([95% \text{CI}: 94.54 \text{ to } 97.27])</td>
<td>82.54 (\pm 18.33) ([95% \text{CI}: 81.04 \text{ to } 88.36])</td>
</tr>
<tr>
<td>Control</td>
<td>30 (\pm 0.00) ([95% \text{CI}: 30 \text{ to } 30])</td>
<td>100 (\pm 0.00) ([95% \text{CI}: 100 \text{ to } 100])</td>
<td>100 (\pm 0.00) ([95% \text{CI}: 100 \text{ to } 100])</td>
</tr>
</tbody>
</table>

LAS = lateral ankle sprain; FAAMadl = activities of daily living subscale of the Foot and Ankle Ability Measure; FAAMsport = sport subscale of the Foot and Ankle Ability Measure.
Figure 1. Hip flexion-extension, knee flexion-extension, ankle inversion-eversion and dorsiflexion-plantar flexion angle during performance of phase 1 and phase 2 of the DVJ task from 200 ms pre-IC to 200 ms post-IC for the involved and uninvolved limbs of the LAS and control groups. Flexion, inversion and dorsiflexion are positive; extension, eversion, and plantar flexion are negative. Black line with arrow = initial contact. Dashed lines = LAS group; continuous lines = control group; black lines = involved limb; grey lines = uninvolved limb. Shaded area enclosed by black line = area of statistically significant between groups difference for the involved limb. Shaded area enclosed by grey line = area of statistically significant between groups difference for the uninvolved limb. Abbreviations: IC = initial contact; DVJ = drop vertical jump; LAS = lateral ankle sprain.
increasing plantar flexion comes reduced bony congruity between the superior aspect of the talus and the inferior aspect of the tibia\textsuperscript{33}, by approximating the ankle joint to a more dorsi-flexed, ‘closed pack’ position in preparation for the landing events during phases 1 and 2 of the DVJ, LAS participants could have been ‘seeking’ to stabilise their ‘vulnerable’ ankle joint using this joint’s structural morphology.

Further proximally, the increase in knee flexion observed in the current study is in agreement with the findings of Caulfield and Garrett in CAI participants during a single-leg jump\textsuperscript{34}. This again may be indicative of a reactive strategy designed to exploit the knee in making the motor apparatus of the LAS participant more flexible on landing, with greater potential for minimising joint stiffness and excessive loading of static ligamentous structures\textsuperscript{35}. However, we urge caution in comparing the results of studies completed in different research laboratories using different methodologies. The advantage of the current study, in the

Figure 2. Sagittal plane joint moment-of-force profiles for the involved and uninvolved hip, knee and ankle during performance of phase 1 and phase 2 of the DVJ task from 200 ms pre-IC to 200 ms post-IC for LAS and control groups. Extension and plantar flexion moments are positive; flexion and dorsiflexion moments are negative. Black line with arrow = initial contact. Dashed lines = LAS group; continuous lines = control group; black lines = involved limb; grey lines = uninvolved limb. Bold abscissa axis indicates area of statistically significant greater trend asymmetry for the LAS group. Shaded area enclosed by black line = area of statistically significant between groups difference for the involved limb. Shaded area enclosed by grey line = area of statistically significant between groups difference for the uninvolved limb. Abbreviations: Mh = Hip moment; Mk = Knee Moment; Ma = Ankle moment; IC = initial contact; DVJ = drop vertical jump; LAS = lateral ankle sprain.
context of the larger longitudinal analysis it forms part of, will be consistency across individuals, the acquisition methods utilised and the task prescribed. The development of a set of prediction rules for recovery based on the current literature is confounded by inconsistencies in these areas, but particularly in the type of task prescribed. Terminal (landing) and non-terminal dynamic (jumping/hopping) movement tasks constrain participants in contrasting ways, and directly comparing the strategies used to complete these tasks must be done with caution. This is evidenced by the fact that Gribble and Robinson actually observed less knee flexion at IC during a jump-landing task, which is in contrast to our findings, yet they observed no differences in hip kinematics, in agreement with our findings, but in contrast to the findings of Brown et al. during a stop-jump task. Importantly, none of the aforementioned studies of CAI populations evaluated movement patterns on the uninvolved limb, making the bilateral nature of the adaptive movements observed in the current study contextually unique. Bilateral deficits have previously been shown to manifest following LAS injury during a static postural control task. Furthermore, evidence of centrally mediated changes of postural control in CAI populations has been demonstrated in separate studies by Evans et al. and Hale et al., suggesting that this acute trauma may lead to impairment of spinal-level and/or supraspinal motor control pathways.

Due to the tendency for many studies in the CAI literature to evaluate the involved limb in isolation during dynamic movements and directly comparing the strategies used to complete these tasks must be done with caution. This is evidenced by the fact that Gribble and Robinson actually observed less knee flexion at IC during a jump-landing task, which is in contrast to our findings, yet they observed no differences in hip kinematics, in agreement with our findings, but in contrast to the findings of Brown et al. during a stop-jump task. Importantly, none of the aforementioned studies of CAI populations evaluated movement patterns on the uninvolved limb, making the bilateral nature of the adaptive movements observed in the current study contextually unique. Bilateral deficits have previously been shown to manifest following LAS injury during a static postural control task. Furthermore, evidence of centrally mediated changes of postural control in CAI populations has been demonstrated in separate studies by Evans et al. and Hale et al., suggesting that this acute trauma may lead to impairment of spinal-level and/or supraspinal motor control pathways.

Due to the tendency for many studies in the CAI literature to evaluate the involved limb in isolation during dynamic movements, the results of the current study supplement the current dearth of evidence examining whether patients with a history of LAS exhibit bilateral deficits in postural control and dynamic balance.

The moment of force profiles presented in the current analysis give an indication of the motor control that caused the movement patterns observed. The LAS participants displayed greater hip extensor dominance on both limbs during phase 1 of the DVJ. The profile for this joint followed a sinusoidal waveform pattern; the flexor moment occurring ≥75 ms

<table>
<thead>
<tr>
<th>DVJ Phase</th>
<th>LAS</th>
<th>Control</th>
<th>p Value</th>
<th>η²</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Involved Limb RIM (BW/sec)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Average</td>
<td>SD</td>
<td>Average</td>
<td>SD</td>
</tr>
<tr>
<td>11.50</td>
<td>4.43</td>
<td>13.40</td>
<td>4.88</td>
<td>.160</td>
</tr>
<tr>
<td>2</td>
<td>13.12</td>
<td>3.28</td>
<td>14.60</td>
<td>3.20</td>
</tr>
<tr>
<td>Uninvolved Limb RIM (BW/sec)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Average</td>
<td>SD</td>
<td>Average</td>
<td>SD</td>
</tr>
<tr>
<td>13.73</td>
<td>5.01</td>
<td>13.26</td>
<td>5.91</td>
<td>.761</td>
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<td>2</td>
<td>14.39</td>
<td>4.22</td>
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<td>Limb Symmetry (%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Average</td>
<td>SD</td>
<td>Average</td>
<td>SD</td>
</tr>
<tr>
<td>11.85</td>
<td>10.13</td>
<td>5.76</td>
<td>4.16</td>
<td>.001*</td>
</tr>
<tr>
<td>2</td>
<td>7.52</td>
<td>6.24</td>
<td>4.35</td>
<td>3.49</td>
</tr>
</tbody>
</table>

Table 2. Rate of Impact Modulation (RIM) with Corresponding Inter-Limb Symmetry Values for the Phase 1 and Phase 2 of the DVJ for the Involved and Uninvolved Limbs of the LAS and Control Groups

Table 3. Kinetic Inter-Limb Trend Symmetry Data for LAS and Control Participants During Phases 1 and 2 of the Drop Vertical Jump Task. Window 1 = 200 ms Pre-Initial Contact (IC) to IC; Window 2 = 100 ms Pre-IC to 100 ms post-IC; Window 3 = IC to 200 ms Post-IC

<table>
<thead>
<tr>
<th>Variable</th>
<th>Trend Symmetry</th>
<th>p-Value</th>
<th>LAS vs Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>DVJ Part</td>
<td>LAS</td>
<td>Control</td>
<td>1</td>
</tr>
<tr>
<td>Hip</td>
<td>1</td>
<td>18.58</td>
<td>25.89</td>
</tr>
<tr>
<td>Knee</td>
<td>1</td>
<td>4.74</td>
<td>5.25</td>
</tr>
<tr>
<td>Ankle</td>
<td>1</td>
<td>21.15</td>
<td>0.66</td>
</tr>
<tr>
<td>Hip</td>
<td>2</td>
<td>21.89</td>
<td>23.75</td>
</tr>
<tr>
<td>Knee</td>
<td>2</td>
<td>21.95</td>
<td>15.69</td>
</tr>
<tr>
<td>Ankle</td>
<td>2</td>
<td>27.50</td>
<td>0.63</td>
</tr>
</tbody>
</table>

LAS = lateral ankle sprain; IC = initial contact. *Denotes statistically significant between groups difference.
post-IC transited to an extensor moment ≈150 ms post-IC, which was greater in the LAS group. The flexor moment may have functioned in both LAS and control participants as a force attenuation strategy adopted following IC. That this then developed into greater extensor dominance in the LAS group may indicate increased activity of the hamstrings and gluteals to extend out of this flexed position during performance of the subsequent maximal vertical jump, rather than depending on the distal activity of the ankle plantar flexors to do so. This cannot be confirmed in the current study however, and as there was no difference in the jump height achieved between the LAS and control groups, neither this coping strategy nor the one displayed by controls can be interpreted as superior for performance, based on the current results.

The greater temporal asymmetry of the hip moment of force profile of LAS participants during phase 1 of the DVJ may be the expression of a strategy adopted in the acute phase of injury to minimise loading to the non-injured limb, which has since become redundant. The development of new motor control strategies will eventually determine these participants’ functional outcome, but it is unclear based on the current dataset as to whether the motor control asymmetries evident at the hip stand to obstruct this. Ultimately, the anomalous movement patterns which likely predict procession to CAI or coper status can only be established at the 1-year time-point. This study serves to identify which variables are most important in recovery. It is likely that some of these movement patterns will emerge as conducive to ‘coping’, and others as maladaptive, which lead to CAI. The limitation of this study is that in isolation, it does not elucidate the main movement pattern or motor control predictors of recovery.

In consideration of the current results, clinicians must recognise the potential for persistence of self-reported functional deficits and disability even 6-months following acute LAS. As part of the rehabilitation protocol, the completion of unilateral and bilateral, dynamic balance tasks which are both terminal and non-terminal in nature, may be required to establish new ‘coping’ motor control and coordination strategies following LAS injury. Future research is required to confirm this speculation.

AUTHORS’ CONTRIBUTIONS

The researchers responsible for the current paper (Mr Cailbhe Doherty, Dr Eamonn Delahun, Dr Chris Bleakley, Prof Jay Hertel, Prof Brian Caulfield, Prof John Ryan, Dr Matt Patterson, and Dr Kevin Sweeney) meet the criteria for authorship; specifically, we have been involved in the conception and design of the study (acquisition of data or analysis and interpretation of data), in drafting the article or revising it critically for important intellectual content, and have contributed to final approval of the submitted version. All those who are entitled to authorship have been included and have approved the final article.

ACKNOWLEDGMENTS

This study was supported by the Health Research Board (HRB_POR/2011/46) as follows: PI – Eamonn Delahun; Co-investigators – Chris Bleakley and Jay Hertel; PhD student – Cailbhe Doherty). The results of the present study do not constitute endorsement by ACSM. No conflicts of interest were associated with the authors and the results of this research.

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