Individuals With Functional Ankle Instability, but not Copers, Have Increased Forefoot Inversion During Walking Gait

Cynthia J. Wright, PhD, ATC; Brent L. Arnold, PhD, ATC, FNATA; Scott E. Ross, PhD, ATC; and Peter E. Pidcoe, PhD, PT

ABSTRACT
Altered gait kinematics in individuals with functional ankle instability (FAI) are thought to contribute to instability; however, research findings are inconsistent. Findings may be clarified with the use of a multisegment foot model and a coper group. Participants included 69 individuals: 23 with FAI, 23 controls, and 23 copers (individuals with a history of ankle sprain but no instability). Forefoot and hindfoot sagittal and frontal plane angles at initial contact (IC) were calculated during gait. For the forefoot and hindfoot, a multivariate analysis of variance tested group differences. For the forefoot in the frontal plane, there was a significant group difference at IC. The FAI group had significantly more inverted ankles than controls, but copers were not significantly different from the FAI or control groups. The lack of difference between the FAI and coper groups may indicate that increased inversion error in FAI does not explain symptoms of instability. [Athletic Training & Sports Health Care. 2013;5(5):201-209.]

A nkle sprains are one of the most common injuries experienced by physically active individuals.1-3 A significant concern following acute ankle sprain is the possibility of ongoing symptoms and long-term disability.4 Approximately 32% to 47% of patients report symptoms of functional ankle instability (FAI), such as sensations of giving way, and subsequent sprains or instability.4,6 These symptoms can decrease quality of life,5 as well as limit physical activity and activities of daily living for years postinjury.6

Because of these potentially serious health-related consequences of FAI, the mechanisms of this clinical pathology have been studied extensively.7-9 One pathological factor that has been associated with FAI is altered joint mechanics.10-15 Joint mechanics can demonstrate how an individual maintains dynamic joint stability during functional activity.16 For example, differences in joint motion may elucidate how an individual with FAI either copes with pathology to dynamically stabilize his or her ankle during activity by adopting movement strategies to increase stability or fails to cope with pathology by using movement strategies that decrease stability.12

Several researchers hypothesized that differences in joint kinematics exist between individuals with FAI and healthy controls.10-15 Walking gait is one task that has received attention, most likely due to its importance in many activities of daily living and because individuals with FAI often complain of giving way sensations while walking on level and uneven surfaces.15 During gait, increased ankle inversion at initial contact (IC) may predispose individuals to ankle inversion injury due to the creation of an inversion moment.17 Although some researchers have found increased ankle inversion at IC in gait,11,12 others have failed to find such differences.13,14 Even when group differences are apparent, it can be difficult to interpret whether changes are positive, negative, or benign adaptations postinjury. Comparing individuals with FAI to copers (ie, individuals who have expe-
rienced an ankle sprain but do not report subsequent instability14,18-27) may help to clarify the current literature by permitting researchers to observe the difference between individuals who incurred a sprain but did not develop instability and individuals who did develop FAI after sprain. These differences could clarify previously unclear findings, possibly identifying kinematic mechanisms by which copers maintain dynamic stability.

A growing number of previous studies of the ankle have grouped participants as copers, noncopers, or healthy controls.14,18-27 However, only 2 articles report on ankle joint kinematics during gait among coper and FAI individuals.14,24 Brown et al14 reported increased ankle joint frontal plane displacement (ie, total range of inversion/eversion) during gait but found no differences between the FAI group and the coper group for any other ankle or knee kinematic variable. This seems to indicate that frontal plane motion is the salient difference between individuals with and without instability. In additional analyses on a subset of the same participants, Brown24 reported differences in maximum foot external rotation and plantar flexion during terminal swing (defined as the 250 ms prior to IC). Unfortunately, these reports did not include a healthy (control) group to make the 3-way comparison; thus, it is unknown whether the reported values for coper and FAI participants were within or outside a normal healthy range.

In addition, all comparisons of walking gait kinematics between individuals with and without FAI have used a single-segment foot model to calculate ankle joint motion.11,14,28 A single-segment foot model uses a modeling assumption that the entire foot moves as a single rigid body. However, in vivo foot and ankle motion is a complex occurrence, with 26 bones articulating across multiple joints during gait. Forefoot and hindfoot motion are not identical during activity; motion occurs across the many joints of the foot.29 Thus, an advantage of a multisegment foot model is that it can capture forefoot and hindfoot motion separately, potentially creating a more accurate and clinically relevant profile of motion. For example, if an FAI individual were to truly have increased hindfoot inversion but decreased forefoot inversion at a specific time point, a single-segment foot model could not capture these specific motions, calculating instead a single value that could cancel out true difference, whereas a multisegment model could capture the motions. Because both forefoot and hindfoot motion could contribute to instability, we thought the use of a multisegment foot model could potentially clarify the currently mixed evidence regarding walking kinematics in individuals with and without FAI.11,14,28

Therefore, the primary purpose of the current study was to capture foot and ankle kinematic data using a multisegment foot model during walking gait among 3 groups of participants (healthy controls, copers, and FAI). We hypothesized that individuals with FAI would have more inversion during gait. We expected to find no difference between our control and coper groups, hypothesizing that because both groups are functionally stable, they would have similar kinematic profiles.

METHOD

Participants
We included 23 participants with FAI (mean episodes of giving way = 5.81 per month, $SD = 8.42$), 23 participants with a history of an ankle sprain but no instability (copers), and 23 participants with no history of ankle sprain or instability (controls) in this study. Twelve men and 11 women composed each group. We matched copers and healthy controls to FAI participants by gender, age ($±10$ years), height ($±10$ cm), and weight ($±15$ kg). In addition, each group had equal numbers of left and right limb–dominant individuals (2 left, 21 right). Participants’ demographics are reported in Table 1. Detailed clinical characteristics (eg, laxity, range of motion), as well as statistical tests on matching criteria, are described elsewhere,23 as this study was part of a larger investiga-

### TABLE 1

<table>
<thead>
<tr>
<th>Study Participant Demographics by Group</th>
<th>MEAN ± STANDARD DEVIATION</th>
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<tbody>
<tr>
<td><strong>DESCRIPTOR</strong></td>
<td><strong>CONTROL</strong></td>
</tr>
<tr>
<td>Age (y)</td>
<td>23.17 ± 4.01</td>
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<tr>
<td>Height (cm)</td>
<td>1.72 ± 0.08</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>68.78 ± 13.26</td>
</tr>
<tr>
<td>CAIT (score)</td>
<td>28.78 ± 1.78</td>
</tr>
</tbody>
</table>

*Abbreviations: CAIT, Cumberland Ankle Instability Tool; FAI, functional ankle instability.

* The FAI group scored significantly lower than the control and coper groups.
tion. This study was approved by the Virginia Commonwealth University’s institutional review board.

Initially, we recruited and screened 83 individuals from a large metropolitan area for participation. These participants reported for a single visit to the Sports Medicine Research Laboratory. After informed consent was obtained, the participants completed an injury history questionnaire and the Cumberland Ankle Instability Tool (CAIT)\textsuperscript{30} to verify inclusion criteria. A customized computer program (Access; Microsoft, Redmond, Washington) recorded and scored participants’ responses for the CAIT. The CAIT has excellent test–retest reliability (ICC\textsubscript{2,1} = 0.96) and is scored from 0 to 30 points, with higher scores indicating higher stability.\textsuperscript{30} The injury history form collected information about the initial ankle sprain injury, symptoms of giving way and sprains, as well as a history of lower extremity fractures or surgeries, and limb dominance. Limb dominance was assessed by asking the individual to self-report his or her dominant, or preferred, limb for activities such as kicking a soccer ball. Participants’ height and weight were also measured and recorded.

FAI participants were required to have a history of \( \geq 1 \) unilateral inversion ankle sprain that required protected weight bearing, immobilization, or limited activity for \( \geq 24 \) hours. In addition, FAI participants had to report multiple episodes of giving way (at least 2 in the past year)\textsuperscript{14} and had to be classified as having FAI, using a cutoff score of \( \leq 27 \) on the CAIT.\textsuperscript{30} Participants in the coper group were required to have a history of a single, unilateral inversion ankle sprain that required protected weight bearing, immobilization, or limited activity for \( \geq 24 \) hours. Copers had no complaints of ankle instability or repeated episodes of giving way and had resumed all preinjury activities without limitation for at least 12 months prior to testing.\textsuperscript{14,20} Similar to previous research,\textsuperscript{31,22} if all other inclusion criteria were met, copers were allowed a single episode of giving way in their lifetime, as long as it occurred at least 12 months prior to study participation. Control participants had no history of ankle sprain or instability in their lifetime. In addition, all participants were required to engage in at least 90 minutes of moderate-to-vigorous physical activity per week for inclusion.\textsuperscript{14,20} Participants self-reported their weekly activity level and intensity using simple recall. Potential participants were excluded if they had a history of surgery or ankle fracture in either lower extremity, any acute symptoms of lower extremity injury on the day of testing, or known systemic disease or condition affecting the musculoskeletal system.\textsuperscript{31}

After reviewing the injury history questionnaire and CAIT scores, 8 participants were excluded for not meeting all study criteria. Another participant was excluded after enrollment because he was unable to follow task instructions. Five participants could not be matched with FAI participants, which left a final total of 69 matched participants (23 per group). Based on pilot data, we calculated that a minimum of 17 participants per group was necessary to detect group differences in our targeted variables. However, because this number was lower than the normal sample size in similar literature,\textsuperscript{11,14,28} we decided a priori to recruit a minimum of 21 participants per group.

Testing was performed on the involved limb (side of the ankle sprain) of the FAI and coper groups and on the matched side of the healthy control group. For FAI individuals with bilateral instability, each participant was asked to subjectively identify his or her most unstable ankle, and that side was designated as the involved limb.

**MOTION CAPTURE**

Markers were placed according to the Oxford multisegment foot model, with additional conventional gait model markers on the knee, hip and pelvis.\textsuperscript{32,33} A multisegment model was selected to capture separate hindfoot and forefoot motion, which may yield more useful information about foot and ankle motion in individuals with and without FAI than the commonly used single-segment model. The examiner (C.J.W.) attached 5 rigid plastic marker plates to participants, using tape prewrap, and attached 34 individual 9.5-mm reflective markers, using double-sided adhesive tape, at specific anatomical landmarks. Marker plates were attached to the posterior pelvis at the height of the posterior superior iliac spine and bilaterally on the distal thigh and shank. Anatomical markers were placed bilaterally on the greater trochanter; anterior superior iliac spine; lateral and medial femoral epicondyles; lateral and medial malleoli; proximal and distal fifth metatarsals; distal second metatarsal; proximal and distal first metatarsal; and the lateral, medial, and posterior calcaneus.
The participant then stood in anatomical position while a static calibration trial was captured. Following the static trial, only the calibration markers were removed (ie, bilateral greater trochanter, lateral and medial femoral epicondyles, medial malleolus, and the posterior superior calcaneus). For all movement trials, a 12-camera Vicon MX motion monitoring system (Oxford Metrics Group, Oxford, United Kingdom) collected the 3-dimensional location of reflective markers at 100 Hz, and two 4060-NC strain-gauge force plates (Bertec Corp, Columbus, Ohio) captured ground reaction forces (GRF) at 1000 Hz. Vicon Nexus 1.4 software (Oxford Metrics Group) synchronized all data collection.

After calibration, we instructed the participant to walk in a straight line across the capture space at a comfortable pace. To promote normal gait, we did not tell the participant that the goal was for IC of the involved limb to occur on one of the force plates. Instead, participants were instructed to initiate gait with the same leg each time, and the examiner adjusted their starting location to promote IC occurring on a force plate. Participants walked at a comfortable, normal pace, with their eyes focused straight ahead. The examiner recorded walking trials until 10 clean force plate strikes occurred. A clean force plate strike was operationally defined as one in which IC and toe-off occurred completely on the force plate.

**DATA PROCESSING**

All kinematic data were processed using Visual3D Professional version 4.00.19 (C-Motion Inc, Germantown, Maryland). Kinematic data for the forefoot and hindfoot were calculated using the segment coordinate systems defined by Stebbins et al as part of a revised Oxford foot model. Euler angles were calculated for the hindfoot relative to the tibia (hindfoot angle) and forefoot relative to the hindfoot (forefoot angle) using the Grood and Suntay sequence. Dynamic hindfoot and forefoot angles were calculated for the involved limb referenced to a standing neutral position (setting all angles equal to zero in a standing neutral position), and all kinematic data were filtered at 12 Hz using a zero-lag, fourth-order, digital Butterworth filter. These methods are highly reliable for calculating adult forefoot and hindfoot motion (ICC = 0.83-0.97, SE of the measure with 90% confidence = 1.09°-1.92°).

Initial contact was identified as the onset of vertical GRF >10 newtons. Toe-off was identified as the first data point after IC where the vertical GRF decreased to <10 newtons. Forefoot and hindfoot positions in the sagittal and frontal planes were recorded at IC. In addition, kinematic data for the entire stance phase (IC to toe-off) was time normalized to 100 data points for graphical comparison among groups. For each participant, data were averaged across 10 trials. For one participant, data collection errors resulted in <10 usable trials. Rather than exclude this participant and unbalance the participant matching, we chose to use the average of the participant’s 8 available trials for analysis. In addition, gait velocity (defined as the average velocity of the pelvis segment’s center of mass) was calculated and averaged across 10 gait trials for each participant.

**STATISTICAL ANALYSIS**

Our primary research aim was to calculate differences in the groups at IC among 4 dependent variables: hindfoot sagittal plane position, hindfoot frontal plane position, forefoot sagittal plane position, and forefoot frontal plane position. Hindfoot and forefoot data were analyzed using 2 separate multivariate analysis of variance (MANOVA), with an independent variable for group (FAI, coper, control) and the dependent variable of plane of motion (sagittal, frontal). If the test for group was significant (\(P < 0.05\)), each dependent variable was interpreted. If the dependent variable was significant, a Tukey post hoc test was conducted on the 3 pairwise comparisons.

Group differences in CAIT and gait velocity were also analyzed using one-way ANOVAs. For these one-way ANOVAs, alpha was set at 0.05, and Tukey post hoc test was used for significant differences. Gait velocity was analyzed because it may affect kinematic variables. Group differences in CAIT were analyzed to ensure that the grouping of participants was appropriate, based on expected group scores. All analyses were completed using SPSS Statistics version 20 software (IBM Corp, Armonk, New York).

**RESULTS**

**Participant Demographics**

Significant differences were noted among groups on the CAIT questionnaire (\(F_{2,66} = 95.377, P < 0.001; \) Table 1).
Tukey post hoc test revealed that the FAI group scored significantly lower than the coper and control groups, which was expected based on inclusion criteria (FAI versus coper group: mean difference = –7.22, SE = 0.65, 95% confidence interval [CI] = –8.78 to –5.66; FAI versus control group: mean difference = –8.26, SE = 0.65, 95% CI = –9.82 to –6.70). The coper and control groups were not significantly different from each other (control versus coper: mean difference = 1.04, SE = 0.65, 95% CI = –0.52 to 2.61).

Walking Task
Gait Velocity. No significant differences were noted in gait velocity among groups (F2,66 = 0.26, P = .774; control group, 1.11 ± 0.11 m/s; coper group, 1.10 ± 0.12 m/s; FAI group, 1.09 ± 0.10 m/s).

Forefoot Motion. Descriptive data for walking kinematics at IC are reported by group in Table 2, and stance phase kinematics are shown in the Figure. The MANOVA for forefoot motion revealed a significant multivariate main effect for group (Wilks’ λ = 0.856, F4,130 = 2.631, P = .037). The effect for group during forefoot sagittal plane motion (ie, dorsiflexion/plantarflexion) was not significant (F2,68 = 0.96, P = .909). However, the effect for group during forefoot frontal plane motion (ie, inversion/eversion) was significant (F2,68 = 4.802, P = .011). Post hoc tests on forefoot frontal plane motion revealed that the FAI group had significantly greater inversion than the control group (P = .008, mean difference = 2.86°, SE = 0.93, 95% CI = 0.64–5.09). No significant differences were noted between the FAI and coper groups (P = .588, mean difference = 1.21°, SE = 0.93, 95% CI = –1.01 to 3.44), nor between the coper and control groups (P = .239, mean difference = 1.65°, SE = 0.93, 95% CI = –0.57 to 3.88).

Hindfoot Motion. The MANOVA for hindfoot motion revealed no significant multivariate main effect for group, indicating that hindfoot angle in the frontal and sagittal planes was not significantly different across the 3 groups tested (Wilks’ λ = 0.938, F4,130 = 1.055, P = .381).

DISCUSSION
We hypothesized that the ankles of individuals with FAI would be more inverted during gait, which is a possible risk factor for instability. We did find greater FAI forefoot inversion at IC compared with controls during walking; however, there were no other differences in hindfoot or forefoot kinematics during gait. Our lack of identified sagittal plane differences is consistent with other reports.11,12,14 Focusing specifically on forefoot inversion during normal walking gait, participants with FAI had 2.86° greater inversion (SE = 0.93, 95% CI = 0.64–5.09) than controls at IC. To our knowledge, we are the only group to report walking kinematics using a multisegment foot model. Thus, we are the only group to report differences specifically in forefoot kinematics. However, our results at the forefoot are similar to those of previous research, which also reported increased ankle inversion at IC, modeling the foot and ankle as a single rigid body.11,12 Our average group difference for forefoot inversion was slightly smaller in magnitude than those studies, which recorded group differences of 3.5° to 6°.11,12 It is pos-

### TABLE 2

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<th>Kinematics (°) at Initial Contact During Walking Task</th>
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<tr>
<td><strong>KINEMATICS</strong></td>
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<tr>
<td>Forefoot</td>
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<tr>
<td>Sagittal plane</td>
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<td>Frontal plane</td>
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<tr>
<td>Hindfoot</td>
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<td>Sagittal plane</td>
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<td>Frontal plane</td>
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**Abbreviations:** CI, confidence interval; FAI, functional ankle instability.

* Positive angle indicates dorsiflexion, negative angle indicates plantarflexion.
* Positive angle indicates inversion, negative angle indicates eversion.
* Denotes statistically significant difference between control and FAI groups (P = .008).
sible that our values are smaller because motion was split between the hindfoot and forefoot segments in our study. One benefit to this split in the current study is that it allows the specific region with altered kinematics to be more precisely located. We originally expected to find the difference in hindfoot inversion, rather than forefoot inversion, because the hindfoot is the segment in contact with the ground at IC. However, forefoot inversion could still affect ankle lateral stability by contributing to overall positioning error as the foot continues to accept weight immediately post-IC (Figure, D). Episodes of instability may not occur exactly at IC but rather in the milliseconds afterward when forefoot positioning may make a greater impact. For this reason, some authors have used a 100- to 200-ms window around IC for analysis\textsuperscript{11,12}; however, this method was not used in the current research because it sharply multiplies the number of data points and statistical tests, increasing the potential for statistical error.

The primary reason to include copers was to provide a comparison group that has experienced the same mechanism of injury—a lateral ankle sprain—but did not develop chronic instability. We expected this to clarify findings from the traditional 2-group model comparing healthy controls versus FAI by adding the profile of a previously sprained but currently stable ankle. Theoretically, the coper group would show no difference from controls regarding variables that contribute to instability and no difference from the FAI group for variables that represent benign postinjury changes. For forefoot inversion at IC, the coper group was not significantly different from the other 2 groups; their mean angle was located between the FAI and control group means. This lack of significant inversion difference at IC between copers and individuals with FAI is consistent with the findings of Brown et al.\textsuperscript{14} In our study, copers were also not significantly different from individuals with FAI, but they showed a trend toward difference from controls (mean difference = 1.65°, SE = 0.93, 95% CI = –0.57 to 3.88). This trend may indicate that the increased forefoot inversion seen during walking gait in individuals with FAI is actually not an active contributor

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Figure. (A) Walking gait mean kinematics from IC to TO (stance) for hindfoot dorsiflexion/plantarflexion, (B) forefoot dorsiflexion/plantarflexion, (C) hindfoot inversion/eversion, and (D) forefoot inversion/eversion. Error bars of ±1 standard deviation are shown for the control group only. The asterisk denotes significant group difference at IC. Abbreviations: FAI, functional ankle instability; IC, initial contact; TO, toe-off.
toward instability but rather a benign change experienced by both coper and FAI individuals after ankle sprain. Alternatively, if forefoot inversion is an active contributor to instability, copers may have an additional stabilizing mechanism that mediates the effect of increased inversion. However, the method used in our study did not lead us to speculate what the nature of this coping mechanism might be.

Another alternative explanation for the observation that the copers’ frontal plane position is aligned between the FAI and control groups is that, although the participants were symptom free for at least 1 year postinjury, copers gradually develop characteristics of FAI over time. The current study did not record the time between initial ankle sprain and study participation in either the coper or FAI groups, and thus cannot demonstrate a relationship between time and kinematic characteristics. However, because individuals with FAI often report symptoms within the initial 6 months to 2 years postinjury, this alternative has distinct limitations. Finally, a potential explanation for our finding that the coper group was aligned between the 2 other groups relates to our inclusion criteria. The current study included copers with a history of only one ankle sprain, whereas some reports have allowed a single recurrence if the individual is stable and symptom free for at least 12 months postinjury. It is possible that copers with a history of only one sprain behave differently (perhaps more like controls) than copers with even a single recurrent sprain (who perhaps appear more like FAI). Future research might benefit from a standardization of coper group inclusion criteria.

As can be seen in the Figure (D), although visually and statistically different at IC, the FAI group mean fell within the error bars of the control group. The clinical implications of inversion angular error of the magnitude found in this study are not clear. According to the work of Konradsen and Voigt, who simulated ankle inversion injury at heel strike in cadavers, it would take a substantial degree of malalignment (8° to 10°) before an inversion moment was created. However, the 2.86° difference between control and FAI groups in the current study is only the average error. The actual error for any one gait cycle varies, and, in fact, previous research has shown that kinematic variability in individuals with FAI is greater than in individuals without instability. Thus, it is possible that an episode of giving way while walking may be precipitated by an abnormally large amount of inversion error during that single gait cycle, and individuals with FAI are then, on average, 2.86° closer to reaching this threshold than are controls. Unfortunately, this theory is difficult to test due to the sporadic nature of episodes of giving way and the low likelihood of one naturally occurring during data capture. Konradsen calculated that given a mean error of 3.4° (0.54° greater than the average error found in the current study) and a normal distribution, the statistical probability of experiencing an error sufficient to cause an inversion moment (ie, >8°) was frequent—approximately 1 of every 1000 steps. The injury potential of an inversion moment does not always translate into actual injury due to dynamic systems that can act to protect the ankle joint. Although this estimate is based on theory, it demonstrates how even a seemingly small error can translate into clinical significance.

LIMITATIONS
The 12 bilateral foot and ankle markers necessary for the Oxford foot model made it impossible for our participants to wear their normal footwear. Thus, the walking trials were completed barefoot. It is possible that kinematics during shod gait differ from barefoot kinematics. Despite this limitation, we believe our group comparisons are valid, as participants in all groups were tested under the same barefoot condition, and our results are similar to previous studies.

IMPLICATIONS FOR CLINICAL PRACTICE
We found increased forefoot inversion at IC in individuals with FAI compared with healthy controls. Previously, increased inversion error in individuals with FAI has been thought to partially explain symptoms of instability. Thus, clinical studies have looked at the effect of various interventions on correcting gait parameters. However, in the current study, copers were not significantly different from FAI individuals, despite the fact that copers do not experience instability. Therefore, in treating individuals with FAI, emphasizing gait training or other interventions, with the goal of decreasing ankle inversion, may not be an effective use of patient or clinician time. Clinicians should instead focus reha-
bilitation and prevention efforts on developing dy-
amic stability mechanisms.

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